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Emissions Characterization of a Heavy-Duty Diesel Truck Engine Operated on Crude and Minimally-Processed Shale Oils

Southwest Research Inst., San Antonio, TX

Prepared for

Environmental Protection Agency, Ann Arbor, MI

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Emissions Characterization of a Heavy-Duty Diesel Truck Engine Operated On Crude and Minimally-Processed Shale Oils

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Three crude shale oils were chosen from six candidates to investigate their possible use as substitutes for No. 2 diesel fuel. Satisfactory hot engine operation was achieved on the crudes using a fuel heating system, allowing emissions characterization during transient and steady-state operation. Regulated gaseous emissions changed little with the crudes compared to diesel fuel; but total particulate and soluble organics increased, and larger injector tip deposits and piston crown erosion were observed. After engine rebuild, two minimally-processed shale oils were run without the fuel heating system, causing no engine problems. Most emissions were higher than for No. 2 fuel using an 80 percent distillate of crude shale oil, but lower using a hydrotreated form of the distillate.

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FOREWORD

The project on which this report is based was initiated by Work Assignment No. 4 of EPA Contract 68-03-3162, received by SwRI on April 25, 1983. The contract was for "Pollution Control Assessment for the Emissions Control Technology Division, Ann Arbor, Michigan." Work Assignment No. 4 of that contract was specifically for "Emission Characterization of Minimally-Processed Oil Shale Fuels." The work was identified within SwRI as Project No. 03-7338-004. Follow-up work continued under EPA Contract 68-03-3192, Work Assignment 2. This other contract is titled, "Fuels Characterization Testing for the Emissions Control Technology Division." Assignment 2 (SwRI Project number 03-7774-002) is titled, "Emissions Characterization of Two Crude Shale Oil Fuels."

The Project Officers for EPA's Technology Assessment Branch during the Work Assignments were Mr. Robert J. Garbe and Mr. Craig A. Harvey. The EPA Branch Technical Representative throughout was also Mr. Harvey. SwRI Project Director was Mr. Karl J. Springer, and SwRI Project Manager was Mr. Charles T. Hare. The SwRI Task Leader and principal investigator for the project was Mr. Terry L. Ullman. Lead technical personnel were Mr. Ed Grinstead and Mr. Ernest Krueger. We would like to express our appreciation to the various companies and personnel for supplying the shale oil crude and minimally-processed shale oils used in this program.

ABSTRACT

Six different crude shale oils were obtained from various sources, and some of the physical and chemical properties of each were determined. Three crude shale oils were chosen to represent two of the "worst" and one of the "best" candidates for successful operation in a heavy-duty diesel engine, the choices being Superior and Paraho DOE, and Geokinetics, respectively. The engine, modified as required to heat the crude shale oil "fuels," operated surprisingly well over both the 13-mode steady-state and transient test cycles, with little change in BSFC.

Emissions measurements were conducted during engine operation on the three selected crude shale oils and on No. 2 diesel fuel. Relative to the diesel fuel, operation on crude shale oils caused little difference in HC and NO_x emissions, but significant increases in CO and total particulate emissions were noted. Some of the near-threefold increases in total particulate were due to increased sulfate emissions, but about 60 percent of the total particulate derived from operation on the crude shale oils consisted of the soluble organic fraction. Emissions of polynuclear aromatic hydrocarbons (PAH) from operation on the crude shale oils were nearly 15 times the level obtained on diesel fuel. "Total cyanide" emissions on the two "worst" candidate materials increased somewhat over the level obtained with No. 2 diesel fuel. Cylinder wall scuffing, erosion of piston crowns, and increased injector tip deposits were noted after operation on the crude shale oils.

The engine was rebuilt and two minimally-processed shale oils, "High Nitrogen Hydrocracker Feed" (HNHF) and "Distillate," were obtained for testing. Emissions from the unmodified rebuilt engine were characterized on both of these minimally-processed shale oils and on No. 2 diesel fuel. On either shale oil, regulated emissions changed relatively little from those established on diesel fuel. In fact, on HNHF, emissions were near the same or below the levels observed on diesel fuel. On Distillate, emissions of total particulate increased along with the level of solubles containing PAH compounds. Aside from slightly greater deposits on the injector tips, no engine damage was noted on either minimally-processed shale oil.

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I. INTRODUCTION

The long-term petroleum supply outlook makes it prudent to characterize emissions from combustion of all important alternative fuel and fuel extender concepts. Their differing compositions are likely to produce changes in exhaust emissions, along with the many effects these concepts may have on transportation and utility engines. One of the alternative fuels explored in this program was crude shale oil. Crude shale oil, sometimes referred to as syncrude, can be altered by various refinery techniques to make it into specification quality fuels. The techniques involved in the upgrading procedures entail considerable cost, which currently place syncrude-derived products well above the competitive costs associated with similar petroleum crude-derived products.

This project covered the use of both crude shale oils and minimally-processed shale oils as "fuel" in a heavy-duty truck-size diesel engine. We were fortunate that six crude shale oils and two minimally-processed shale oils, in quantities of 110 gallons each, were made available for this project. After measuring the properties of the "fuels," three of the six crude shale oils were introduced to the engine. The raw shale oil crudes were first filtered to remove solids, and the engine's entire fuel handling system was heated and pressurized to assure satisfactory fuel delivery. The engine was successfully operated over both steady-state and transient test procedures on the crude shale oils for characterization of exhaust emissions. Following engine rebuild and break-in, both transient and steady-state emissions were measured while the engine was operated on two minimally-processed shale oils. None of the crude or minimally-processed shale oils used in this program represent any intended consumer-ready products since these materials were not refined to any existing specifications. They were of interest because it was conceivable that products like these might be offered to consumers in the future.

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II. SUMMARY

This program investigated the possibility of operating a heavy-duty truck-size diesel engine on both crude and minimally-processed shale oils, and it characterized the resulting exhaust emissions. The engine used in this work was an International Harvester DT-466B, which developed 210 hp with 87 lb/hr of No. 2 diesel fuel (DF-2, coded EM-528-F). Six crude shale oils, originating from various retorting methods and various sources of oil shale rock, were obtained for use in this program. The six crude shale oils obtained were: Paraho "SwRI," Paraho DOE, Superior, Geokinetics, Union and Occidental. These names essentially designate the source and the retorting processes used. The Paraho, Superior, and Union samples were from above ground retorts, and the Occidental and Geokinetics samples were from in-situ retorts. Two minimally-processed shale oils were obtained from Geokinetics, Inc. These intermediate products were part of an 82,000 barrel refining operation set up to produce specification JP-4, DF-2 and gasoline using crude shale oil stock from both Anvil Points Defense Fuels Supply Center and Geokinetics, Inc.

Many of the physical and chemical properties of both the crude and minimally-processed shale oils were determined, and are presented in Section IV of this report. Of six crude shale oils, the Geokinetics and Superior crude oils were selected for use during a preliminary "fuel" screening, and represented the "best" and "worst" candidate materials for successful engine operation on crude shale oil, respectively. Surprisingly, the engine operated well on the crude shale oils and developed near rated power during the preliminary fuel screening on both shale oils. The engine had been modified in that the fuel circuit was pressurized, and the entire fuel system was heated to approximately 200-300°F such that the viscosity of the crude shale oil was kept near that of DF-2 (approximately 3 centistokes). The engine and fuel system were brought up to the necessary temperature on DF-2, then switched over to the heated crude shale oil. Since fuel system heating was required for use of the shale crude oils, which had pour points near 80°F, only "hot" engine operation was possible (cold-start would have been impractical). Based on steady-state experience during the preliminary fuel screening of Geokinetics and Superior, engine operation was expanded to include transient test operation and an additional test fuel, Paraho DOE. This fuel was considered "next-to-the-worst" candidate for successful engine operation on the basis of its physical and chemical properties.

The two minimally-processed shale oils were a "Distillate Shale Crude" (representing approximately the lower-boiling 80 percent of the crude shale oil) and a "High Nitrogen Hydrocracker Feed" (Distillate which had been hydrotreated). The High Nitrogen Hydrocracker Feed (HNHF) actually contained very little nitrogen (0.05 percent nitrogen) and most impurities (ash, fines, water, sulfur) had been substantially reduced. Both of these intermediate refinery products required no special heating or modifications for use by the engine. The engine operated well on both minimally-processed shale oils and "cold-start" operation was also good.

Regulated and unregulated emissions were determined over transient test operation of the DT-466B on DF-2; on Superior, Geokinetics, and Paraho DOE

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crude shale oils; and the two minimally-processed shale oils. In addition, regulated gaseous emissions were determined over the steady-state 13-mode test procedure on these four fuels, along with smoke opacities over the FTP for smoke. Table 1 summarizes the composite values of emissions measured over these various test procedures, using the DF-2 and the three selected crude shale oils. Corresponding detailed test results may be found in the "Results" section of the report (Section V). Table 2 summarizes the composite values of emissions measured over the various test procedures using DF-2 and the two minimally-processed shale oils. Detailed test results for these two fuels may be found in the "Results" section of the report (Section VII).

A. Crude Shale Oil

For 13-mode steady-state operation on the three crude shale oils, hydrocarbon emission levels were about the same as obtained on DF-2. Generally, increases in HC emissions during steady-state idle and light-load operation were offset by slight reductions during high power operation. Substantial increases in HC emissions were noted over the lightly loaded transient test cycle run on all three crude shale oils, and were an average of 73 percent above the level obtained on DF-2. Carbon monoxide emissions over both test procedures on DF-2 were nearly doubled by use of the Superior and Paraho DOE crude shale oils. On the Geokinetics material, CO emissions were an average of 45 percent greater than obtained on DF-2 over both test procedures. Emissions of NO_x were about the same for all fuels, despite higher levels of nitrogen contained in the three shale oils. Surprisingly, BSFC on the crude materials was also very similar to that obtained on DF-2, and the engine operated well with no adjustment of fuel injection timing to optimize performance.

In addition to general hydrocarbon emissions measurements by use of specified procedures, emissions of selected hydrocarbon species were also determined over transient operation. Of the "total individual hydrocarbons" summarized in Table 1, ethylene and propylene were most abundant, and their emissions were notably greater on the Superior and Paraho DOE crude shale oils than on DF-2. Ammonia emissions were 39 percent greater on Geokinetics, and near the same level as on DF-2 for both the Superior and Paraho DOE shale oils. Cyanide emissions which were 0.91 mg/kW-hr on DF-2, increased substantially to 9.8 mg/kW-hr (a factor of 10.8) on Geokinetics, and to 27 mg/kW-hr (a factor of 30) on Superior and Paraho DOE shale oils. Aldehyde emissions on the three crude shale oils, mostly consisting of formaldehyde, generally increased by a factor of 2.2 over the level obtained on DF-2. Similarly, use of shale oil increased emissions of phenols over the DF-2 base level; however, the levels were low, and variability associated with the analytical procedure is relatively greater for the small levels of phenols detected. Odor, generally associated with a wide range of organic species, was measured by instrumentation (CRC'S DOAS) to determine relative total intensity of aroma (TIA). TIA for transient operation on crude shale oils averaged 2.38, compared to a level of 1.26 determined for operation on DF-2.

The total particulate emissions, 0.95 g/kW-hr on DF-2 over the transient cycle, increased by a factor of 2.2 on the Geokinetics to 2.09 g/kW-hr. Total particulate for operation on both Superior and Paraho DOE crudes increased by

TABLE 1. SUMMARY OF EMISSIONS FROM IH DT-466B ON DF-2, AND THREE CRUDE SHALE OILS

Fuel		Emissions by Fuel and Test Procedure							
		DF-2 EM-528-F		Superior EM-584-F		Geokinetics EM-586-F		Paraho DOE EM-585-F	
Federal Test Procedure (FTP)		13-Mode	Transient[a]	13-Mode	Transient[a]	13-Mode	Transient[a]	13-Mode	Transient[a]
Hydrocarbons, HC g/kW-hr, (g/hp-hr)		1.26 (0.94)	1.27 (0.95)	1.31 (0.98)	2.15 (1.60)	1.13 (0.84)	2.17 (1.62)	1.22 (0.91)	2.29 (1.71)
Carbon Monoxide, CO g/kW-hr, (g/hp-hr)		3.02 (2.25)	3.12 (2.33)	6.80 (5.07)	6.66 (4.97)	4.41 (3.29)	4.51 (3.36)	6.92 (4.41)	5.66 (4.22)
Oxides of Nitrogen, NO_x[b] g/kW-hr, (g/hp-hr)		11.38 (8.49)	11.05 (8.24)	10.33 (7.70)	10.82 (8.06)	11.16 (8.32)	10.57 (7.88)	10.61 (7.91)	11.77 (8.78)
Brake Specific Fuel Consumption kg fuel/kW-hr, (lb/hp-hr)		0.271 (0.446)	0.271 (0.445)	0.274 (0.450)	0.282 (0.465)	0.282 (0.463)	0.274 (0.450)	0.277 (0.456)	0.271 (0.446)
Unregulated Emissions									
Total Individual HC mg/kW-hr		--	170	--	350	--	210	--	280
Ammonia mg/kW-hr		--	72	--	64	--	100	--	74
Cyanide mg/kW-hr		--	0.91	--	27	--	9.8	--	27
Total Aldehydes mg/kW-hr		--	170	--	320	--	390	--	410
Total Phenols mg/kW-hr		--	2.0	--	2.2	--	13	--	7.9
Total Intensity of Aroma, TIA (by LCO)		--	1.26	--	2.53	--	2.32	--	2.2
Total Particulate g/kW-hr, (g/hp-hr)		--	0.95 (0.71)	--	3.11 (2.32)	--	2.09 (1.56)	--	2.86 (2.13)
Sulfate, $SO_4^=$ mg/kW-hr, (% of Particulate)		--	34 (3.6)	--	200 (6.4)	--	120 (5.7)	--	130 (4.7)
Soluble Organic Fraction (SOF) mg/kW-hr, (% of Particulate)		--	380 (40.5)	--	1850 (59.6)	--	1250 (59.8)	--	1820 (63.8)
Total Measured PAH g/kW-hr		--	55	--	940	--	680	--	920
Ames Response[c] (10^3 rev./plate)/kW-hr	No[d]	--	290	--	1600	--	1400	--	1600
	Yes[d]	--	140	--	2600	--	1300	--	2400

[a] Hot-start transient cycle only

[b] Based on bag measurement

[c] Average of brake specific response from all 5 strains, TA97A, TA98, TA100, TA102, and TA98NR

[d] Metabolic activation status

TABLE 2. SUMMARY OF EMISSIONS FROM IH DT-466B ON DF-2, AND TWO MINIMALLY-PROCESSED SHALE OILS

Fuel	Emissions by Fuel and Test Procedure					
	DF-2 EM-597-F		HNHF EM-599-F		Distillate EM-600-F	
Federal Test Procedure (FTP)	13-Mode	Transient[a]	13-Mode	Transient[a]	13-Mode	Transient[a]
Hydrocarbons, HC g/kW-hr, (g/hp-hr)	0.94 (0.70)	1.16 (0.86)	0.83 (0.62)	0.90 (0.67)	0.94 (0.70)	1.36 (1.01)
Carbon Monoxide, CO g/kW-hr, (g/hp-hr)	2.24 (1.67)	2.80 (2.08)	1.82 (1.36)	2.37 (1.77)	2.43 (1.81)	3.23 (2.41)
Oxides of Nitrogen, NO_x[b] g/kW-hr, (g/hp-hr)	11.63 (8.67)	11.46 (8.55)	10.04 (7.48)	9.64 (7.18)	12.23 (9.12)	11.80 (8.80)
Brake Specific Fuel Consumption kg fuel/kW-hr, (lb/hp-hr)	0.249 (0.410)	0.257 (0.422)	0.248 (0.407)	0.249 (0.409)	0.262 (0.430)	0.257 (0.421)
Unregulated Emissions						
Total Individual HC mg/kW-hr	--	140	--	120	--	130
Ammonia mg/kW-hr	--	96	--	22	--	< 37
Cyanide mg/kW-hr	--	11	--	4.3	--	12
Total Aldehydes mg/kW-hr	--	210	--	120	--	190
Total Phenols mg/kW-hr	--	< 1.1	--	1.1	--	3.0
Total Intensity of Aroma, TIA (by LCO)	--	1.60	--	1.86	--	1.95
Total Particulate g/kW-hr, (g/hp-hr)	--	0.80 (0.60)	--	0.57 (0.43)	--	0.93 (0.70)
Sulfate, $SO_4^=$ mg/kW-hr,(% of Particulate)	--	53 (6.6)	--	4.8 (0.8)	--	80 (8.6)
Soluble Organic Fraction (SOF) mg/kW-hr, (% of Particulate)	--	290 (36.2)	--	220 (37.7)	--	470 (50.5)
Total Measured PAH g/kW-hr	--	54	--	55	--	170
Ames Response[c] (10^3 rev./plate)/kW-hr — No[d]	--	360	--	100	--	260
Yes[d]	--	250	--	100	--	210

[a] Composite transient

[b] Based on bag measurement

[c] Average of brake specific response from all 5 strains, TA97A, TA98, TA100, TA102, and TA98NR

[d] Metabolic activation status

about a factor of 3 over DF-2 to 3.11 and 2.86 g/kW-hr, respectively. The soluble organic fraction (SOF) of the total particulate from transient operation on DF-2 accounted for 40 percent by mass, whereas on the crude shale oils, the SOF in the total particulate accounted for nearly 60 percent. Sulfate emissions on DF-2 were 33.8 mg/kW-hr, increasing by a factor of 3.5 on Geokinetics, 4.0 on Paraho DOE, and 5.0 on the Superior crude shale oil. Emissions of measured polynuclear aromatic hydrocarbons (PAH) were substantially greater on all three of the crude shale oils than on DF-2. Total measured PAH increased by about a factor of 17 over DF-2 levels on Superior and Paraho DOE, and by a factor of 12 on Geokinetics. Results from bioassay of the SOF indicated about a five-fold increase in brake specific response for the three crude shale oils compared to DF-2 when no metabolic activation was used. With metabolic activation, brake specific response of SOF derived from Geokinetics was 10 times that for DF-2 and brake specific response of SOF from both Paraho DOE and Superior crudes were almost 18 times that for DF-2.

Deposits on injector nozzle tips were noticeably greater after use of the three crude shale oils. These deposits were particularly noticeable after running on Geokinetics and Paraho DOE. Teardown and inspection of the engine revealed potential problems with cylinder wall lubrication, and also piston top damage (similar to that associated with operation on gasoline). No damage to the pump or injectors was attributed to the crude shale oil itself, but some damage to spring-operated mechanisms may have been the result of heating the crude shale oil to near 300°F.

B. Minimally-Processed Shale Oil

The DT-466B heavy-duty diesel engine was rebuilt following completion of experiments run with crude shale oil. Following break-in, another emissions baseline on DF-2 was obtained for the engine prior to testing of the two minimally-processed shale oils. Emissions results from this latest baseline are given in Table 2 along with results obtained on the two minimally-processed shale oils. After engine rebuild, regulated emissions were established for both 13-mode steady-state and cold- and hot-start transient test operation. Hydrocarbons and CO were slightly lower, while NO_x emissions were slightly higher than the baseline levels established prior to hot-start transient operation on the crude shale oils. These relatively minor changes in regulated emissions and BSFC coincide with the direction of change expected due to improved fuel delivery and combustion associated with the engine rebuild.

Composite HC emissions from the DT-466B, while operated on High Nitrogen Hydrocracker Feed (HNHF), were 12 and 22 percent lower than the baseline levels over both the 13-mode and transient FTP tests, respectively. On the Distillate, no change in 13-mode composite HC emissions was noted, but transient composite HC emissions were 17 percent greater due to increased HC emissions at light load conditions. On HNHF, composite 13-mode and transient CO emissions decreased by 19 and 15 percent from the second baseline, respectively; but on the Distillate shale oil, CO increased by 8 and 15 percent, respectively. Similarly, composite emissions of NO_x decreased by 8 and 16 percent on HNHF over 13-mode and transient FTP testing, but on Distillate, composite NO_x emissions increased by 5 and 3 percent, respectively. A slight BSFC improvement (decrease) was noted for transient composite operation on

HNHF (3%). Over 13-mode operation on Distillate, BSFC increased 5 percent compared to operation on DF-2. These changes in BSFC may not be significant.

Specific techniques were used to determine emissions of selected hydrocarbon species over transient FTP operation. Of the "total individual hydrocarbons" summarized in Table 2, ethylene and propylene were most abundant, but surprisingly somewhat lower on both minimally-processed shale oils than on DF-2. Similarly, emission of ammonia on both minimally-processed shale oils was below the level obtained on DF-2. No ammonia above the minimum detectable level (37 mg /kW-hr) was noted when Distillate shale oil was used, which was somewhat unexpected considering that the fuel contained 1.23 percent fuel nitrogen. Cyanide emissions were about the same level on Distillate as noted on DF-2, but relatively low on HNHF. Compared to operation on DF-2, aldehyde emissions, consisting mainly of formaldehyde and acetaldehyde, were somewhat lower on Distillate and lower still on HNHF. No phenols above the minimum detectable levels were noted on either DF-2 or HNHF, and only very slight emissions were noted on the Distillate shale oil. Odor, measured by an instrumental technique, showed only a slight increase over the level obtained on DF-2 when the minimally-processed shale oils were used.

The total particulate emissions, 0.80 g/kW-hr on DF-2 for the transient FTP, increased by 16 percent (to 0.93 g/kW-hr) on Distillate shale oil, but decreased by 29 percent (to 0.57 g/kW-hr) on HNHF. The soluble organic fraction (SOF) on both DF-2 and HNHF was about 37 percent, but somewhat higher at about 51 percent on Distillate shale oil. Sulfate emissions on DF-2, which contained about 0.35 percent sulfur by weight, were 53 mg/kW-hr; and they increased 51 percent on Distillate, which contained about 0.52 percent sulfur. On HNHF, which contained less than 0.01 percent sulfur, sulfate emissions were 91 percent lower than the level noted on DF-2. Analyses of SOF indicated that the levels of various polynuclear aromatic hydrocarbons (PAH) were generally about the same on either DF-2 or HNHF, but increased by a factor of 3.1 on Distillate shale oil. Results from bioassay of the SOF samples indicate that the brake specific response was actually lower for the HNHF and Distillate than for the DF-2, with or without metabolic activation.

C. General Comments

It is very interesting that a multi-cylinder heavy-duty engine could be operated at all on any of the crude shale oils made available for this program. The fact that these crude shale oils would allow engine operation for at least a limited number of hours before combustion chamber damage occurred is in itself useful from the standpoint of emergency fuel scenarios. Although only moderate increases in regulated emissions were observed from use of the crude shale oils, higher emissions of particulate and several of the unregulated pollutants indicate that use of crude shale oils could potentially cause environmental problems which would have to be examined. Increased emissions of total particulate and several of the PAH compounds during this program demonstrates potential problems.

In contrast, use of the minimally-processed shale oils posed few problems with either fuel handling or emissions. Even though some increases in emissions were noted with the Distillate shale oil, such as higher total particulate and

PAH associated with increased emissions of SOF, the engine apparently would operate well on this minimally-processed fuel. Operation on HNHF, hydrotreated Distillate, caused no increases in any of the emissions measured in this program (except for TIA). The problem in utilizing this hydrotreated material may be that it is more valuable as a blending agent to enhance less desirable diesel fuels than it is as a neat fuel substitute for DF-2. Aside from exhaust emissions with use of these minimally-processed shale oils, research into safety, exposure, distribution and storage problems, and other factors may discourage the use of these materials. If it appears that use of these minimally-processed shale oils is feasible, then additional effort should be directed toward obtaining exhaust emissions and engine durability data on other engines likely to be involved in such use.

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III. TEST PLAN, PROCEDURES, AND TEST ENGINE

This section describes the test plan followed in evaluating both crude and minimally-processed shale oils. Descriptions of the steady-state and transient test procedures are given. Analytical procedures used in the analysis of various emission samples are described. The test engine used in this work is described along with a description of the fuel system normally used with this engine.

A. Test Plan

The statement of work for the initial program contained five Tasks. Task 1 was to obtain a minimum of two barrels of each of several crude or minimally-processed shale oil products. With the assistance of the Project Officer, six different crude shale oil products were obtained, and two minimally-processed shale oils were also secured. Properties of the crude shale oil "fuels" were determined under Task 1. Properties of the two minimally-processed shale oils were determined under follow-on contract effort.

Task 2 of the initial program was to obtain an engine for the test work, along with provision for repair or rebuild if necessary. At the onset, the worst case assumption was made that the engine would seize or the injection pump would fail when the crude shale oil was introduced. The engine supplied for the program was an EPA-owned International Harvester DT-466B turbocharged, direct-injection engine. Follow-on work with the minimally-processed shale oils was also conducted on this engine (following rebuild).

Task 3 of the initial program was to determine which of the crude shale oils could be run, following necessary engine modification to permit operation. This task was also to result in recommending to EPA a maximum of three shale materials of minimal quality that could be run in the engine for emissions testing during Tasks 4 and 5.

Tasks 4 and 5 of the initial program and the main purpose of the follow-on contract effort were essentially to characterize exhaust emissions from the test engine operated on diesel fuel as well as on the selected shale materials. The exhaust emission characterization was to include regulated as well as many unregulated emission species of current interest.

Under the initial program effort, these Tasks were incorporated into the following test plan.

- Set up DT-466B engine on steady-state engine dynamometer, run performance checks using DF-2.

- Obtain representative samples of crude shale materials and conduct analysis for fuel properties.

- Filter crude shale materials, obtain samples and conduct comparable analysis for fuel properties.

- Establish baseline 13-mode gaseous and smoke emissions on DF-2, and check condition of the engine.
- Modify engine/fuel system as needed to conduct preliminary fuel screening on most likely successful candidate crude shale material.
- Establish comparable steady-state information on DF-2 and check condition of engine.
- Modify engine/fuel system as needed to conduct preliminary fuel screening on least likely successful candidate crude shale material.
- Establish comparable steady-state information on DF-2 and check condition of engine.
- Review data with the Project Officer and proceed to detailed emissions characterization under transient test conditions.
- Set up engine on transient-capable dynamometer.
- Establish baseline emissions as outlined in Table 3 on DF-2, and check condition of engine.
- Modify engine/fuel system as needed to measure emissions as outlined in Table 3 on 1st-choice crude shale material, and check condition of engine.
- Modify engine/fuel system as needed to measure emissions as outlined in Table 3 on 2nd-choice crude shale material, and check condition of engine.
- Modify engine/fuel system as needed to measure emissions as outlined in Table 3 on 3rd-choice crude shale material, and check condition of engine.

TABLE 3. PROPOSED HOT-START TRANSIENT EMISSIONS CHARACTERIZATION FOR THE IH DT-466B ON DF-2 AND SHALE OILS

Gaseous Emissions	Particulate Emissions
HC[h]	Total Particulate[c]
CO[f,h]	Sulfate
NO_x[f,h]	Metals & Sulfur
CO_2[f,h]	C,H,N
Ammonia	
Cyanide	
Aldehydes[a]	Solubles[d,e]
Phenols	
IHC[f]	PNA's and 1-nitropyrene
DOAS[b]	C,H,N
	Boiling Range
	Ames Test (150 mg)[g]

Visible Smoke

Smoke FTP
13-Mode

---

[a] Aldehydes using Liquid Chromatograph Procedure
[b] Using DF-2 standard
[c] Determine by 47 mm Pallflex
[d] Solubles from 20x20 Pallflex filters
[e] Solvent methylene chloride
[f] Analysis of gaseous bag sample
[g] Ames test (5 strain, with/without activation-2 way) on DF-2 and shale oils
[h] 13-mode

Under the follow-on program effort, the test plan included:

- Rebuild DT-466B engine, set up engine on transient capable dynamometer, run break-in, run performance checks using DF-2.

- Obtain representative samples of minimally-processed shale oils, and conduct analyses for fuel properties if needed to supplement available data.

- Establish baseline emissions (including cold- and hot-start transient) as outlined in Table 4 on DF-2 (following 20 hours maximum power stabilization) and check condition of engine.

- Modify engine/fuel system as needed to measure emissions (including cold- and hot-start transient) as outlined in Table 4 on both minimally-processed shale oils and check condition of engine after each.

TABLE 4. PROPOSED TRANSIENT EMISSIONS CHARACTERIZATION FOR THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Gaseous Emissions

HC[a,l]
CO[a,j,l]
NO_x[a,j,l]
CO_2[a,j,l]
Ammonia[b]
Cyanide[b]
Aldehydes[c,e]
Phenols[b]
IHC[c,j]
DOAS[b,f]

Particulate Emissions

Total Particulate[a,g]
Sulfate[c]
Metals & Sulfur[c]
C,H,N[b]

Solubles[c,h,i]

PNA's and 1-nitropyrene[b]
C,H,N[b]
Boiling Range[b]
Ames Test (150 mg)[d,k]

Visible Smoke

Smoke FTP
13-Mode

---

[a] Determined over each run
[b] Determined over 1 cold-start and 1 hot-start tests
[c] Determined over 2 cold-start and 2 hot-start tests (replicate)
[d] Determined from weighted sample
[e] Aldehydes using Liquid Chromatograph Procedure
[f] Using DF-2 standard
[g] Determined by 47 mm Pallflex filters
[h] Solubles from 20x20 Pallflex filters
[i] Solvent: methylene chloride
[j] Analysis of gaseous bag sample
[k] Ames test (5 strain-2 way) on DF-2 and shale oils
[l] 13-mode

B. Test Procedures

Emissions from the International Harvester DT-466B heavy-duty diesel engine were determined over both steady-state and transient engine operation. Steady-state operation and measurement techniques were based on the 1979 13-mode Federal Test Procedure (FTP).(3) Transient operation and measurement techniques were based on the 1984 FTP and 1986 Proposed FTP, which included particulate.(1,2) Smoke emissions were measured according the Federal procedure for smoke testing.(3)

1. 13-Mode FTP and 7-Mode Steady-State Test Procedures

The 13-mode test procedure is an engine exercise which consists of 13 individual modes of steady-state operation. Starting with a fully-warmed engine, the first mode is an idle condition. This idle is then followed by 2, 25, 50, 75 and 100 percent load at intermediate speed, and another idle mode; then rated speed - 100, 75, 50, 25, and 2 percent of full load, followed by a final idle mode. Intake air, fuel, and power output are monitored along with other data to be used in calculating modal emissions rates. A 13-mode composite emission rate is calculated on the basis of modal weighting factors as specified in the Federal Register.(3)

During preliminary fuel screening of the crude shale oils, emissions were measured over 7 modes of steady-state operation instead of 13 modes. This 7-mode procedure is a variation of the 13-mode procedure and consists of only the 2, 50 and 100 percent loads at intermediate and rated speeds, plus one idle condition. On the basis of the 13-mode FTP weighting factors, 7-mode composite emissions were computed using weighting factors shown in Table 5.(4) As the number of modes decreases, each modal point represents more time in mode and a wider range of power; thus the weighting for each of the 7 modes must be increased compared to its factor for 13-mode use. For both the 13-mode and the 7-mode procedures, the idle condition accounts for 20 percent of the composite value (equivalent to 20 percent of operating time).(3,4)

TABLE 5. LISTING OF 13-MODE AND 7-MODE WEIGHTING FACTORS

13-Mode			7-Mode	
Mode	Engine Speed/Load, %	Wt. Factor	Mode	Wt. Factor
1	Idle	0.067		
2	Intermediate/2	0.080	1	0.12
3	Intermediate/25	0.080		
4	Intermediate/50	0.080	2	0.16
5	Intermediate/75	0.080		
6	Intermediate/100	0.080	3	0.12
7	Idle	0.067	4	0.20
8	Rated/100	0.080	5	0.12
9	Rated/75	0.080		
10	Rated/50	0.080	6	0.16
11	Rated/25	0.080		
12	Rated/2	0.080	7	0.12
13	Idle	0.067		
	Composite	1.00	Composite	1.00

2. Transient Test Procedure

Transient engine operation was performed in accordance with the 1984 Transient FTP for Heavy-Duty Diesel Engines.(1) The procedure specifies a transient engine exercise of variable speed and load, depending on the power output capabilities of the test engine. The cycle requires relatively rapid dynamometer control, capable of loading the engine one moment and motoring it the next. The system used in this program consisted of a GE 150 hp motoring/200 hp absorbing dynamometer coupled to a Midwest 175 hp eddy current (absorbing) dynamometer, with a suitable control system fabricated in-house. The test operator's control station contains the Compudas computer, operator keyboard, analog recorder, and CVS control panel.

The 1984 Transient cycle is described in the Federal Register(1) by means of percent maximum torque and percent rated speed for each one-second interval, for a test cycle of 1199 seconds duration. The 20-minute transient cycle, developed from heavy-duty truck data, is composed of four five-minute segments. The four segments are described below:

Transient Cycle Segment	Time, sec.
New York Non-Freeway (NYNF)	297
Los Angeles Non-Freeway (LANF)	300
Los Angeles Freeway (LAF)	305
New York Non-Freeway (NYNF)	297

In order to generate the transient cycle for the DT-466B engine, the engine's full power curve was obtained from 500 rpm to maximum no load engine speed. Data from this "power curve," or engine map, was used in conjunction with the specified speed and load percentages to form the transient cycle.

A graphic presentation of speed and torque commands which constituted an FTP transient cycle for a particular 250 hp diesel engine is given in Figure 1 for illustration purposes. For this example, the resulting cycle work was 15.66 hp-hr (11.68 kW-hr), based on a peak torque of 650 ft-lbs (880 N•m) and a rated speed of 2200 rpm. The relatively large negative torque commands shown in the figure are to insure that the "throttle," or rack control, goes closed for motoring operation.

A "Transient FTP Test" consists of a cold-start transient cycle and a hot-start transient cycle. The same engine control or command cycle is used in both cases. For the cold-start, the diesel engine was operated over a "prep" cycle, then allowed to stand overnight in an ambient soak temperature of 20 to 30°C (68 to 86°F). The cold-start transient cycle normally begins when the engine is cranked for cold start-up. Upon completion of the cold-start transient cycle, the engine is shut down and allowed to stand for 20 minutes. After this hot soak period, the hot-start cycle begins with engine cranking.

Due to the necessity of bringing the crude shale oil, injection pump, injectors, and the overall fuel system to relatively high operating temperatures (220°F minimum), it was not practical to obtain cold-start emissions or performance data during operation on crude shale oil. All test work with crude shale oil was carried out on a warm engine. Hot-start sampling was begun with the engine idling on the crude shale oil after switch over from DF-2 with the engine running. In contrast, both minimally-processed shale oils had properties which allowed cold-start operation. Hence, emissions were characterized over both cold- and hot-start transient operation according to the 1984 Transient FTP.

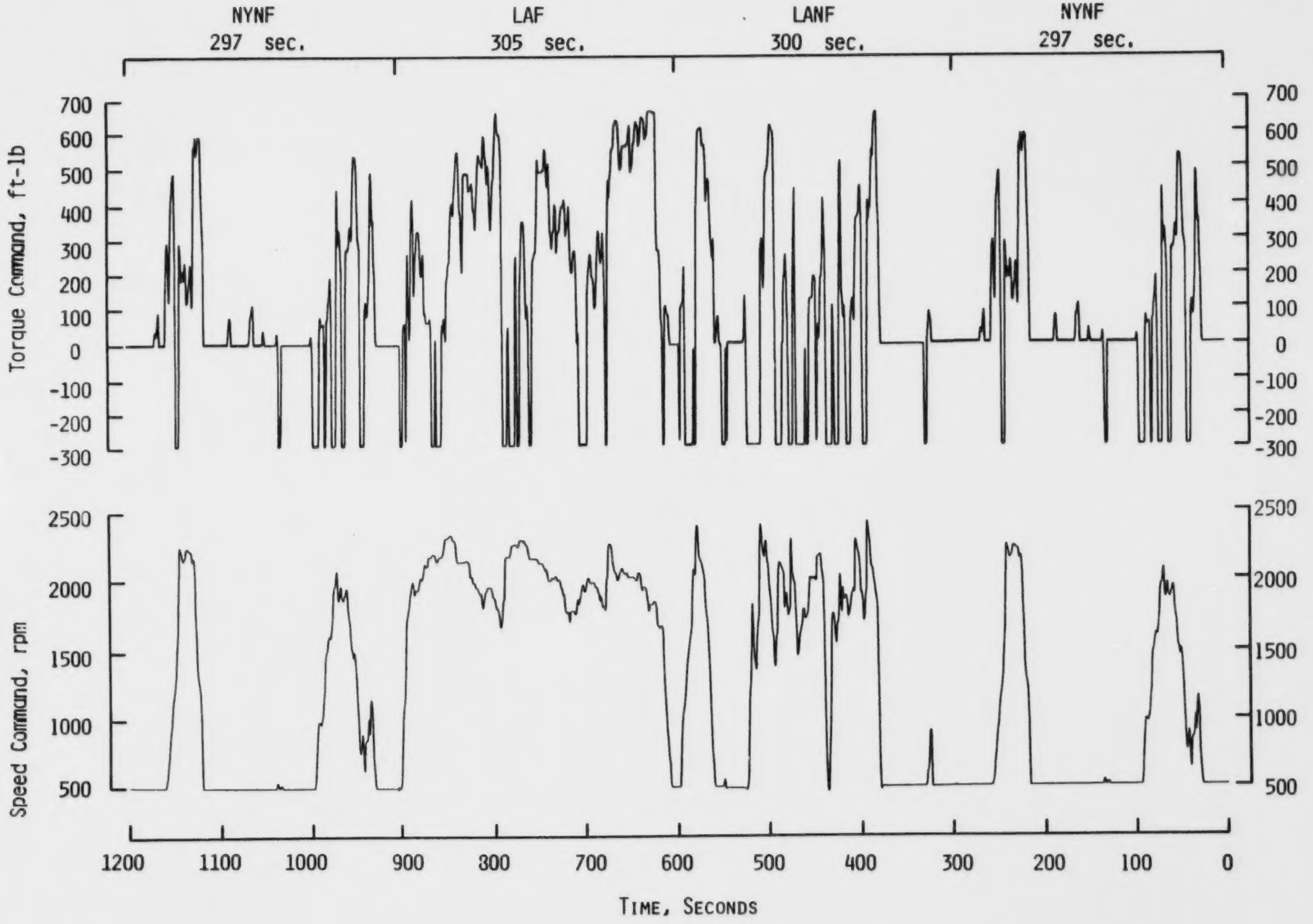


Figure 1. Graphic representation of torque and speed commands for the 1984 Transient FTP cycle for a 250 hp at 2200 rpm diesel engine

All engines react somewhat differently to the transient cycle commands due to both cycle and engine characteristics. In order to judge how well the engine follows the transient cycle command, engine responses are compared to engine commands and several statistics are computed. According to the Federal Register,(2) the following regression line tolerances in Table 6 should be met:

TABLE 6. REGRESSION LINE TOLERANCES

Parameter	Speed	Torque	Brake Horsepower
Standard Error or Estimate (SE) of Y on X	100 rpm	13% of Maximum Engine Torque	8% of Maximum Brake Horsepower
Slope of the Regression Line, M	0.970 1.030	0.83-1.03 Hot 0.77-1.03 Cold	0.89-1.03 (Hot) 0.87-1.03 (Cold)
Coefficient of Determination, R^2	0.9700[a]	0.8800 (Hot)[a] 0.8500 (Cold)[a]	0.9100[a]
Y Intercept of the Regression Line, B	±50 rpm	±15 ft lb	±5.0 brake horsepower

[a]minimum

In addition to these statistical parameters, the actual cycle work produced should not be more than 5 percent above, or 15 percent below, the work requested by the command cycle. If the statistical criteria are not met, then adjustments to throttle servo linkage, torque span points, speed span points, and gain to and from error feedback circuits can be made in order to modify both the engine output (through servo motor control of engine throttle lever) and the dynamometer loading/motoring characteristics. During work with both crude and minimally-processed shale oils, no problems with statistical criteria were noted, even though the cycle control was based on the engine map from operation on DF-2.

Since cold-start testing was not possible on crude shale oil, all transient test results were given for hot-start transient only. Transient composite results from cold- and hot-start transient testing on baseline and minimally-processed shale oils were computed by the following:

$$\text{Brake specific Emissions} = \frac{1/7\ (\text{Mass Emissions, Cold}) + 6/7\ (\text{Mass Emission, Hot})}{1/7\ (\text{Cycle Work Cold}) + 6/7\ (\text{Cycle Work, Hot})}$$

3. Smoke FTP

Smoke emissions were determined using a PHS end-of-stack smokemeter. This smokemeter measures the percent of light extinction by the total exhaust plume from the engine. Smoke testing was conducted with the same inlet and exhaust restrictions used for the 13-mode gaseous emissions test procedure.

The smoke test consists of running three consecutive smoke cycles. Figure 2 illustrates the speed trace of the engine over one such cycle. Throttle position during the cycle is either fully closed or opened (except for the 1st acceleration which calls for a 200 rpm increase in engine speed). Following a warm-up, smokemeter calibration, and a 10-minute maximum power warm-up, the first smoke cycle is begun. The first cycle starts with a 5-minute idle period, then a quick 200 rpm acceleration (1st acceleration), then a full throttle acceleration to at least 85 percent of rated speed (2nd acceleration), then close throttle until the engine speed drops to intermediate speed. At this point, the throttle is fully opened and maximum power is held for approximately 55 seconds, and with the throttle still held fully open, the engine is loaded down such that the rpm drops gradually to intermediate speed (lug down). At this point the smoke cycle is completed and the engine is brought to idle to begin the next cycle. Three of the cycles must be run back-to-back before the smoke test sequence is completed.

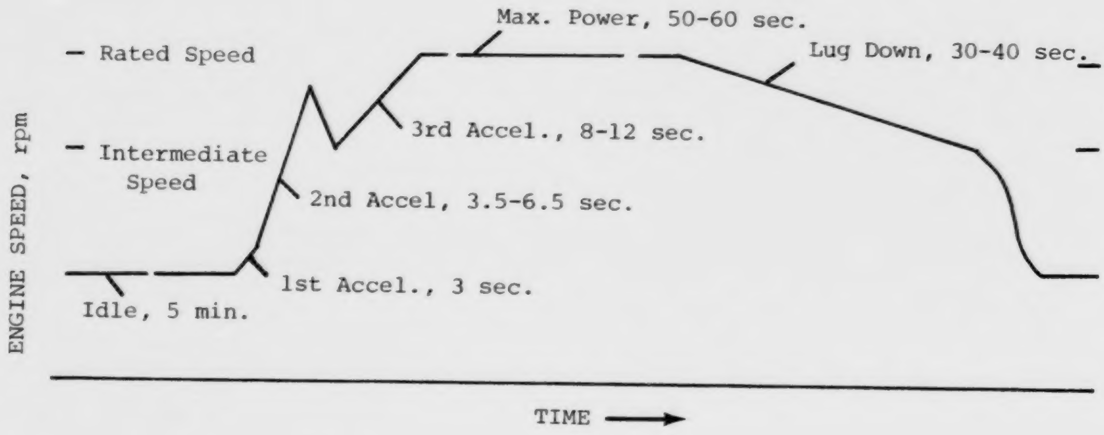


Figure 2. Engine speed trace of one smoke test cycle

This procedure simulates a truck stopped, accelerating through a gear, upshifting to another gear at intermediate speed and accelerating to rated engine speed. (The speed range from rated speed to intermediate speed is usually designated as the driver's normal operating range). The smoke test also includes a lug down portion, simulating a top gear, full throttle deceleration in engine speed from rated speed to intermediate speed, such as would occur if a truck was climbing a hill without downshifting to a lower gear. Results from the smoke test are given in terms of percent smoke opacity and are divided into three factors. The "A" factor represents acceleration smoke, the "B" factor represents lug down smoke (hill climb), and the "C" factor represents peak smoke (puffs during early portions of rapid opening of the throttle). The human eye detects smoke opacities near or about 3-4 percent opacity level.

The smoke test chart results are validated and read according to 86.879-13 of the Federal Register. Essentially the acceleration and lug portions of each cycle are divided into 1/2 second intervals. The 15 highest smoke opacity readings from the three accelerations of each cycle are recorded. The average of these 45 smoke opacity readings yield the "A" factor, or acceleration smoke factor. Similarly, the 5 highest readings from the lug down portion of each cycle are determined. The average of these 15 smoke opacity readings yield the "B" factor, or lug factor. The "C" factor, or peak smoke factor, is determined by taking the three highest of the 15 values selected from the acceleration portions of each cycle. The average of these 9 smoke opacity readings yield the "C" factor. Of the three factors, the lug or "B" factor is perhaps the most repeatable, followed by the acceleration or "A" factor. The peak factor is substantially more variable.

C. Analytical Procedures

The analytical systems used for each category of emission measurements are described in this section. The section is divided into two parts, the first dealing with gaseous emissions characterization and the second with total particulate emissions and the constituents of the total particulate. Gaseous emissions of HC, CO, NO_x and 13-mode smoke were determined from raw exhaust during preliminary fuel screening using steady-state operation on DF-2 and crude shale oils. Once the preliminary screening was completed, gaseous emissions of HC, CO, NO_x and some unregulated pollutants were characterized over hot-start transient engine operation on DF-2 and selected shale oils using a constant volume sampler (CVS). Although the transient procedure only specifies one dilute exhaust Tedlar sample bag, the system used in this program uses one sample bag for each segment. This allows a better understanding of individual cycle segment contributions to the total regulated gaseous emissions measured.

Unregulated gaseous emissions included ammonia, cyanide, aldehydes, selected individual hydrocarbons, phenols and odor. Particulate emissions included determination of the total particulate mass, and its content of sulfate, metal, carbon, hydrogen, nitrogen, and sulfur. The fraction of the total particulate soluble in methylene chloride, or soluble organic fraction (SOF), was determined and analyzed for its content of carbon, hydrogen, nitrogen, PNA, and nitropyrene. The boiling range of the SOF was also determined. In addition, samples of SOF were submitted for Ames testing.

During steady-state or modal engine exercises, regulated and some unregulated gaseous emissions can be sampled from the raw exhaust stream since a representative and proportional sample can be obtained. Obtaining proportional samples during transient engine operation, however, required the use of a constant volume sampler (CVS).(1,2)

A single-dilution CVS having a capacity from 1,000 to 12,000 SCFM was operated at approximately 3200 SCFM during transient testing of the DT-466B. This single-dilution CVS utilizes a 46 inch diameter tunnel with a total length of 57 feet. The system uses two 47 mm T60A20 Pallflex filters (in series) to determine the particulate mass emission and the respective filter efficiency. Auxiliary 47 mm filter positions were used to collect additional total particulate samples for elemental analysis and sulfate. Three 20x20 inch filters were used to collect total particulate in quantities sufficient to establish the percentage of SOF, and to characterize the soluble fraction.

1. Gaseous emissions

Hydrocarbon emissions from a diesel engine are most difficult to determine because they are generally low in concentration and typically include a variety of hydrocarbon species, many of which are higher molecular weight, making them susceptible to loss in the sampling system. Besides unburned fuel species, total hydrocarbons contain varying concentrations of aldehydes, straight chain hydrocarbons, and complex aromatics.

During the 13-mode or 7-mode steady-state procedure, the sample train was heated to 375°F in order to insure that the higher boiling range hydrocarbons were able to reach the heated flame ionization detector (HFID). The raw exhaust sample was filtered through a heated filter prior to reaching the pump and HFID (all kept to 375°F). Since the sample remained heated throughout the system, the measurement was on a "wet" basis. No water trap was provided in the HC sample train. Thirteen-mode calculations based on H/C mole ratio, f/a measured, f/a stoichiometric ratio, measured emissions, and intake air humidity were used to calculate a wet HC correction factor to account for water vapor volume contained in the raw exhaust sample.

Hydrocarbons over the transient tests were measured using the specified heated sample train and heated flame ionization detector (HFID). A Beckman 402 HFID was used. During transient test procedures, a continuous dilute sample taken from the main dilution tunnel was integrated for total hydrocarbons. The heated HC probe (kept to 375°F) and overflow calibration technique used in total HC measurements are specified by the transient FTP. Details about measurement of the regulated gaseous emissions over the transient procedure may be found in Reference 1.

Emissions of CO over the 13-mode or 7-mode steady state procedure were relatively straightforward to measure, using a non-dispersive infrared detector (NDIR) instrument. For most diesel engines, CO emissions are typically low. The sample of raw exhaust gases was passed through a water trap (water and ice bath) to reduce the influence of water vapor on the measured CO concentration. For all practical purposes, the CO emission concentration over the steady-state procedure is considered to be on a dry basis.

Carbon monoxide and CO_2 concentrations of bag samples, taken over the transient cycle, were measured using non-dispersive infrared detector (NDIR) instruments using the sample train specified in the Federal Register.(1) The CO measurement is of interest because it is a regulated pollutant. The CO_2 measurement is of interest because it is used in the calculation of fuel usage by carbon balance along with the CO and HC emissions.

Emissions of NO_x are more difficult to determine accurately due to the combination of NO and NO_x species. During steady-state test procedures, the raw exhaust sample was kept heated to 375°F until it reached a water trap (isopropyl alcohol and dry ice bath). This trap was used to remove not only water vapor, but also a variety of unknown species which can cause instrument interferences. The NO_x concentration of this dried sample stream was determined by a chemiluminescence (CL) instrument. Over the transient test, the NO_x emissions were determined from dilute sample bags. The NO_x concentration of each bag was determined by a CL instrument using the specified sample train. For both steady-state and transient test procedures, the sample train included an NO converter and an ozonator, which essentially insured that all NO molecules were converted to excited NO_2^*, which gives off light and is read accordingly.

NO_x emissions are dependent on the cylinder combustion process and are affected by intake humidity. Calculations in the 13-mode procedure correct for the influence of humidity on NO_x emission concentrations. The NO_x correction factor for the steady-state procedure is based on a humidity level of 75 grains per pound of dry air and inlet air temperature of 85°F, and is somewhat dependent on the f/a ratio. In the case of transient test operation, the engine intake humidity and temperature were controlled to 60-90 grains/lb of dry air and 68-86°F, so a correction factor of 1 was used to process the transient data (specified by the Federal Register, Reference 1).

For the steady-state procedure, composite gaseous emissions and BSFC are calculated from the individual modal data according to the Federal Register Section 86.345-79.(3) Each mode is processed to obtain emission rates, power (corrected to 29.00 in Hg at 85°F inlet air temp.), and brake specific fuel consumption (BSFC). Composite emissions were computed using weighting factors described in the previous section. BSFC over the transient test procedures was computed on the basis of carbon balance via HC, CO and CO_2 emissions and utilized the percent of fuel carbon present in the test fuel.

Ammonia was determined by passing a proportional sample of CVS-diluted exhaust gases through a glass impinger containing dilute H_2SO_4 maintained at ice bath temperature. A portion of the acidified impinger contents was analyzed for the protonated form of NH_4^+ by use of an ion chromatograph. The concentration of ammonia was determined by comparison of the exhaust sample concentration to that of an ammonium sulfate standard solution.(5)

The collection of total cyanide was accomplished by bubbling CVS-diluted exhaust through glass impingers containing a 1.0 N potassium hydroxide absorbing solution maintained at ice bath temperature. An aliquot of the absorbing reagent was treated with KH_4PO_4 and Chloramine-T. A portion of the resulting cyanogen chloride was injected into a gas chromatograph equipped with an electron capture detector (ECD). External CN^- standards were used to quantify the results.(5)

Some selected individual hydrocarbons (IHC) were determined from dilute exhaust bag samples taken over the cold-start and hot-start transient cycles using the CVS. A portion of the exhaust sample collected in the Tedlar bag was injected into a four-column gas chromatograph using a single flame ionization detector and dual sampling valves. The timed sequence selection valves allowed the baseline separation of air, methane, ethane, ethylene, acetylene, propane, propylene, benzene, and toluene.(5)

Aldehydes and ketones were determined using an improved 2,4-dinitrophenylhydrazine (DNPH) method.(6) Dilute samples were taken from the main CVS dilution tunnel during transient testing. A heated Teflon sample line and filter were maintained at 190°C (375°F). The procedure consists of bubbling filtered exhaust gases, dilute or raw, through glass impinger traps containing a solution of DNPH and perchloric acid in acetonitrile. An aliquot of the sample is directly analyzed on a high-performance liquid chromatograph for formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, crotonaldehyde, isobutyraldehyde, methylethylketone, benzaldehyde, and hexanaldehyde.

Phenols, which are hydroxyl derivatives of aromatic hydrocarbons, were measured using an ether extraction procedure detailed in Reference 5. Dilute samples were taken from the main CVS dilution tunnel during transient operation only. Dilute exhaust samples were filtered and collected in impingers containing aqueous potassium hydroxide. The contents of the impingers were acidified with sulfuric acid, then extracted with ethyl ether. This extract was injected into a gas chromatograph equipped with an FID in order to separate 11 different phenols ranging in molecular weight from 94.11 to 150.22.

Total intensity of aroma (TIA) was quantified by using the Coordinating Research Council Diesel Odor Analytical System (DOAS). CVS-diluted exhaust was drawn off through a heated sample train and into a trap containing Chromosorb 102. The trap was later eluted and injected by syringe into the DOAS instrument, which is a liquid chromatograph that separates an oxygenate fraction (liquid column oxygenates, LCO) and an aromatic fraction (liquid column aromatics, LCA). The TIA values are defined as:

$$\mathrm{TIA} = 1 + \log_{10}(\mathrm{LCO}, \mu g/\ell)$$

or

$$\mathrm{TIA} = 0.4 + 0.7 \log_{10}(\mathrm{LCA}, \mu g/\ell)$$

A.D. Little, the developer of the DOAS instrument, has related this fraction to TIA sensory measurement by the A.D. Little odor panel.(7) TIA computed from LCO is preferred. The system was intended for raw exhaust samples from steady-state operating conditions, but for this program, dilute samples of exhaust were taken in order to determine a TIA value for transient operation. Since dilute samples were taken, the resulting values of LCO and LCA were increased in proportion to the 12:1 dilution ratio and TIA calculated.

2. Particulate Emissions

Particulate emissions were determined from dilute exhaust samples utilizing various collection media and apparatus, depending on the analysis to be performed. Particulate has been defined as any material collected on a fluorocarbon-coated glass fiber filter at or below a temperature of 51.7°C (125°F), excluding condensed water.(2) The 125°F temperature limit and the absence of condensed water dictates that the raw exhaust be diluted, irrespective of engine operating mode. The temperature limit generally required dilution ratios of approximately 12:1 (total mixture:raw exhaust).

Total particulate samples were collected on 47 mm Pallflex T60A20 fluorocarbon-coated glass fiber filter media. Gravimetric weight gain, representing collected particulate, was determined to the nearest microgram after the filter temperature and humidity were stabilized. This weight gain, along with CVS flow parameters and engine data, were used to calculate the total particulate mass emissions of the engine under test.

Smoke and total particulate are related in that the relative level of smoke opacity indicates the relative level of particulate. The absence of smoke, however, does not indicate the absence of particulate. Smoke was determined by the end-of-stack EPA-PHS smokemeter, which monitored the opacity of the raw exhaust plume as it issued from the 4 inch diameter exhaust pipe. Smoke opacity was determined for 13-mode operation, and for the smoke FTP.(3)

Since total particulate, by definition, includes anything collected on fluorocarbon-coated glass fiber filter media, there has always been a interest in finding out what constitutes the "total particulate." The following paragraphs describe the methods and analysis used to determine some of the properties of the total particulate.

Sulfate, originating from the combustion of sulfur-containing fuel, was collected as part of the particulate matter in the form of sulfate salts to sulfuric acid aerosols. A 47 mm Fluoropore (Millipore Corp.) fluorocarbon membrane filter with 0.5 micron pore size was used to collect the sample. This total particulate sample is ammoniated to "fix" the sulfate portion of the particulate. Using the barium chloranilate (BCA) analytical method, the sulfates are leached from the filter with an isopropyl alcohol-water solution (60% IPA). This extract is injected into a high pressure liquid chromatograph (HPLC) and pumped through a column to scrub out the cations and convert the sulfate to sulfuric acid. Passage through a reactor column of barium chloranilate crystals precipitates out barium sulfate and releases the highly UV-absorbing chloranilate ions. The amount of chloranilate ion released is determined by a sensitive liquid chromatograph UV detector at 320-313 nanometers. "Sulfate" should be understood to mean $SO_4^=$ as measured by the BCA method.(5)

Carbon, hydrogen, metals, and other elements that make up the total particulate are also of interest. A sample of "total particulate" was collected on 47 mm Type A (Gelman) glass fiber filter media for the purpose of determining the carbon, hydrogen and nitrogen weight percentages. This analysis was performed by Galbraith Laboratories using a Perkin-Elmer Model 240B automated thermal conductivity CHN analyzer. A sample of total particulate matter was also collected on a 47 mm Fluoropore filter for the determination of trace elements such as calcium, aluminum, phosphorus, and sulfur by x-ray fluorescence. This analysis was conducted at the EPA, ORD laboratories in Research Triangle Park, North Carolina using a Siemens NRS-3 X-ray fluorescence spectrometer.

Diesel particulate generally contains significant quantities of condensed fuel-like or oil-like hydrocarbon aerosols generated during incomplete combustion. In order to determine to what extent total particulate contains these various hydrocarbons, large particulate-laden filters (20x20 inch) were washed with an organic solvent, methylene chloride, using 500 ml soxhlet extraction apparatus. The dissolved portion of the "total particulate" carried off with the methylene chloride solvent has been referred to as the "soluble organic fraction" (SOF). All filter handling, extraction processes, and handling of concentrated SOF were carried out according to EPA recommended protocol.(8) The SOF may be composed of anything carried over by the extraction process, so its composition is also of interest. Generally the SOF contains numerous organic compounds, many of which are difficult to isolate and quantify. Most diesel SOF has been shown to be mutagenic using the Ames test.

The boiling range of the SOF was determined by SwRI's Fuels and Lubricants Research Division using a high-temperature variation of ASTM-D2887-73. Approximately 100 mg of the SOF was dissolved in solvent and an internal standard (C_9 to C_{11} compounds) was added. This sample was then submitted for instrumental analysis of boiling point distribution.

The analysis of the polynuclear aromatic hydrocarbons (PAHs) (pyrene, chrysene, benz(a)anthracene, benzo(e)pyrene, and benzo(a)pyrene) was performed using a μ Bondapak NH_2 column for SOF sample cleanup, a Vydac analytical column for individual component separation and a fluorescence spectrophotometer for PAH detection.(9) A portion of the SOF (20-50 mg) was redissolved in methylene chloride and solvent-exchanged into 1 ml of isooctane. Thirty μl of this extract solution was separated into three fractions using a semi-preparative μ Bondapak NH_2 column (7.6 mm x 25.0 cm) and a hexane mobile phase (2.5 ml/min). The first fraction contained pyrene, and was collected 8.25 minutes to 10.5 minutes after sample injection. The second fraction contained benz(a)anthracene and chrysene (10.5 to 13 minutes), and the third contained benzo(e)pyrene, and benzo(a)pyrene (13 to 15.5 minutes).

The material in each of these fractions was solvent-exchanged into 1 ml of acetonitrile and analyzed using a Vydac analytical column with a solvent program of 75% acetonitrile in water for 10 minutes (12 for pyrene), followed by programming to 100% acetonitrile at 2% per minute and holding at 100% acetonitrile for 10 to 12 minutes. A solvent flowrate of 0.8 ml/min was maintained for the duration of the analysis.

A fluorescence spectrophotometer was used to detect and quantify each of the PAHs in the three fractions. Fluorescence excitation and emission wavelengths were selected for each PAH to give maximum sensitivity in relation to interfering compounds. The following excitation and emission settings were used in the analyses:

Fraction 1 -	Pyrene: excitation 330 nm, emission 395 nm
Fraction 2 -	Benz(a)anthracene: excitation 280 nm, emission 389 nm Chrysene: excitation 260 nm, emission 365 nm
Fraction 3 -	Benzo(e)pyrene: excitation 330 nm, emission 395 nm Benzo(a)pyrene: excitation 383 nm, emission 430 nm

The determination of 1-nitropyrene was accomplished by using a method developed by the U.S. Environmental Protection Agency.(10)

1-nitropyrene was collected as part of total particulate on 20x20 inch Pallflex filters. A portion of the dried soluble organic from the total particulate was redissolved in a 50:50 mixture of methylene chloride/methanol. The analysis of 1-nitropyrene was accomplished using a reduction catalyst (by which nitropyrene is converted to aminopyrene) and a High Performance Liquid Chromatograph (HPLC) coupled to a fluorescence detector.

Two reduction catalysts were used in the system, one to remove oxidative compounds from the solvent, and one to convert the nitropyrene to the highly fluorescent aminopyrenes. Two Zorbax ODS analytical columns were also employed in the system. The first column separated any aminopyrenes present in the extract from the nitropyrenes before they entered the reduction catalyst. The second ODS column further separated the reduced nitropyrenes (aminopyrenes at this point) from other interfering compounds in the extract. The excitation and emission wavelength settings for the detector were 360 and 430 nm, respectively. Several operating parameters for the system are listed below:

Mobile Phase	77% Methanol/23% water (V:V)
Mobile Phase Flow Rate	1.1 milliliters per minute
Catalyst Columns	3 inch x 4.6 mm column packed with ground -up (70 mesh) 3-way catalyst from U.S. automobile
Catalyst Temperatures	80°C
Analytical Columns	25 cm x 4.6 mm Zorbax ODS Column before catalyst 15 cm x 4.6 mm Zorbax ODS Column after catalyst
1-Nitropyrene Elution Time	38 minutes
Detector	Fluorescence with 360 nm excitation wavelength and 430 nm emission wavelength settings.

Carbon and hydrogen contents of the SOF were determined by Galbraith Laboratories using a Perkin-Elmer Model 240B automated thermal conductivity CHN analyzer. Another portion of the SOF was submitted to SwRI Fuels and Lubricants Research Division for nitrogen analysis by chemiluminescence.

Samples of SOF were submitted for Ames testing. The Ames test, as employed in this program, refers to a bacterial mutagenesis plate assay with Salmonella typhimurium according to the method of Ames.(11) This bioassay determines the ability of chemical compounds or mixtures to cause mutation of DNA in the bacteria, positive results occurring when histidine-dependent strains of bacteria revert (or are mutated) genetically to forms which can synthesize histidine on their own. Samples of SOF were submitted to Southwest Foundation for Biomedical Research, for testing with and without metabolic activation on tester strains TA97A, TA98, TA100, TA102 and TA98NR (nitroreductase deficient).

D. Test Engine

The test engine used in this program and shown in Figure 3 was an International Harvester Model DT-466B heavy-duty diesel engine, serial number 466T T2U011139. This engine had been used by EPA to obtain information on methanol fueling. Following completion of that program, the engine was rebuilt, to the extent that the original (diesel) pistons and rings were installed, the cylinders were honed, the main bearings were replaced, and the original head and a rebuilt diesel fuel injection pump were refitted to the engine. The engine was operated for a short time to confirm satisfactory operation and to serve as break-in before shipping it to SwRI.

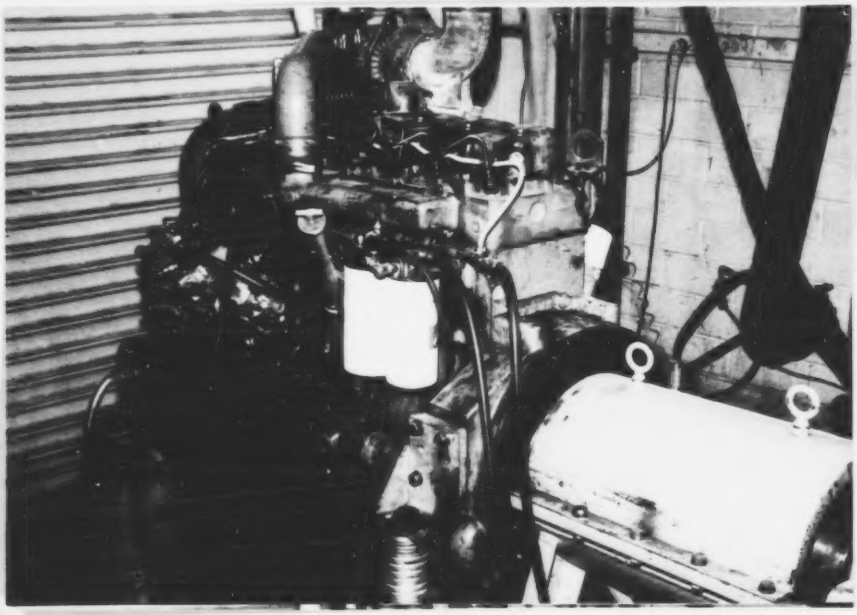


Figure 3. International Harvester DT-466B heavy-duty diesel engine

This engine utilized an American Bosch Model 100 Series injection pump (Pump No. 6A-100A-9402-D1, Serial No. 7565865). The pump is a single plunger design of constant stroke, distributing plunger, sleeve control type. It is governor-controlled with automatic variable timing. The injection pump was removed from the engine for the purpose of flow check and calibration. After calibration, the pump was re-installed with a static timing of 16 1/2 °BTDC (equivalent to setting as received).

This turbocharged, 6 cylinder in-line diesel engine of 466 cubic inch displacement developed 210 horsepower at a rated speed of 2600 rpm, with a fuel consumption of 87.3 lbs/hr of DF-2 (No. 2 emissions diesel fuel, SwRI fuel code, EM-528-F). At an intermediate speed of 1800 rpm, the engine developed 152 horsepower and a torque of 445 lb-ft with 56.7 lbs/hr of DF-2. Intake and exhaust restrictions were approximately 25 in. H_2O and 2.2 in. Hg, measured at rated power condition, respectively. Figure 4 shows the schematic of the fuel circuit normally used on the DT-466B.

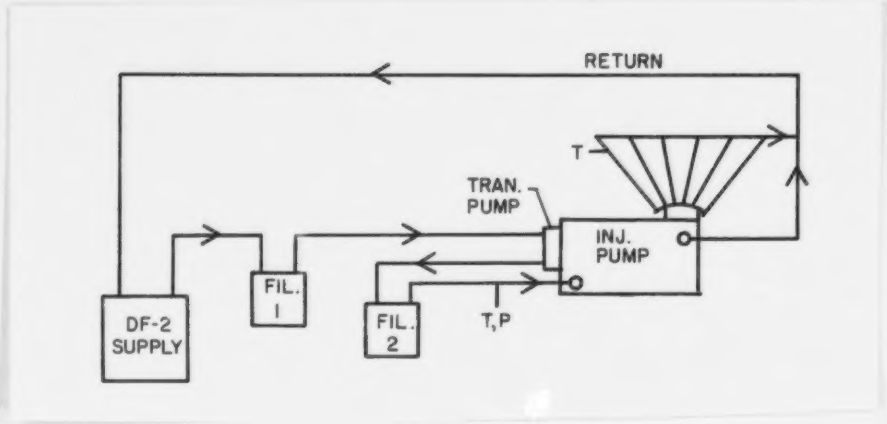


Figure 4. Schematic of Normal Fuel Circuit of IH DT-466B

Fuel from the supply tank is drawn through the primary fuel filter (Filter No. 1), by the transfer pump mounted at the rear of the injection pump. The transfer pump pressurizes the fuel to a range of 30 to 60 psi (depending on load and rpm), and pushes the fuel through the secondary fuel filter and on to the injection pump. A calibrated amount of fuel is delivered to the individual injectors. Injector spillage is collected and returned to the supply tank. Excess fuel supplied to the injection pump is returned to the supply tank through a restricted pump return line.

IV. DESCRIPTION OF SHALE OILS

This section describes the various shale oil products made available for engine test work in this program. Some background information is given on each oil, along with properties of the individual shale oils. Sections A and B of Part IV are presented for background on obtaining crude shale oil from oil shale (rock). Much of the discussion, and many of the tables and figures in Sections A and B were taken from References 12, 13, 14, and 15. In addition, that portion of Reference 12 used herein was contributed by J.E. Sinor of Cameron Engineers on the basis of materials contained in Reference 13. Section C presents various properties determined for each of the six crude shale oils. Selection of three crude shale oils for engine operation was based on these properties. Section D gives a brief background and presents the properties of the two minimally-processed shale oils used for engine operation in the program.

A. General Background Information on Shale Oils

Oil shale generally refers to a wide variety of laminated sedimentary rocks containing organic matter that can be released only by destructive distillation. Oil shales contain over one-third mineral matter and are thus distinguished from coal, which commonly contains only minor amounts of minerals. The organic portion, a mixture of complex chemical compounds, carries the term "kerogen" (derived from Greek and meaning "producer of wax"). Kerogen is not a definite material, however, and kerogens from different shales are dissimilar.

Oil shale deposits vary greatly in richness, and ironically, the deposits being commercially explored are not necessarily the richest. In general, rich deposits have little lamination and are commonly of massive structure. For example, the Green River deposit from Colorado is particularly consolidated and impervious.

While worldwide deposits of oil shale are very extensive, in-place reserves of oil are subject to a large degree of uncertainty due to the fundamental difference in character of the oil shales and because only very preliminary exploration efforts have been made to define the deposits. Total worldwide reserves, based on oil in-place, have been estimated by the Bureau of Mines to amount to 334×10^5 barrels. Almost two-thirds of these currently known in-place reserves are located in the United States. Geographically, they are distributed as shown in Figure 5. Reserve quantities and shale assays are given in Table 7.

Eastern shales contain less organics per ton than Green River (Colorado) shale, and the organics they do contain yield a lower percentage of oil than the Western shale. In fact, the Antrim shale which Dow proposed to investigate contains only about 10 gallons/ton. Thus, considerably greater quantities of Eastern shale would have to be retorted to yield the same amount of liquid product as is produced by a given quantity of Green River shale.

The organic constituents of Eastern oil shales typically yield about the same amount of gaseous products per pound as Green River shale, and in some cases slightly more. Therefore, a shale grade as determined by the modified Fischer Assay method, which accounts only for liquid products, tends to be somewhat misleading regarding the amount of gaseous products recoverable.

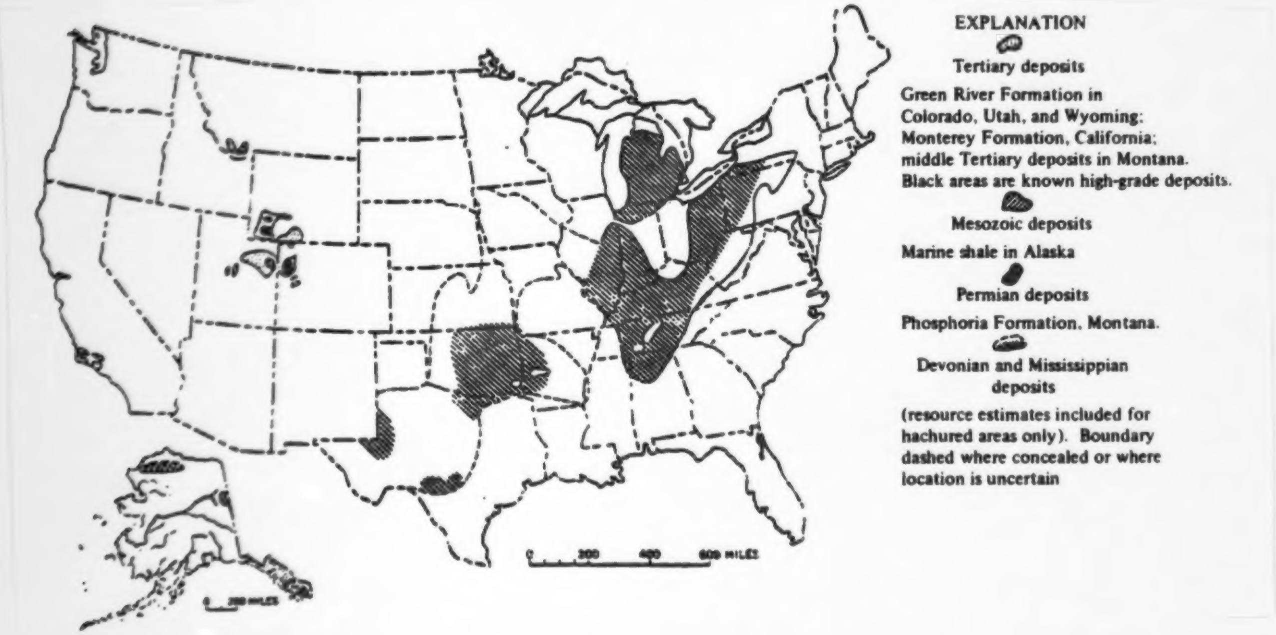

EXPLANATION
Tertiary deposits
Green River Formation in Colorado, Utah, and Wyoming; Monterey Formation, California; middle Tertiary deposits in Montana. Black areas are known high-grade deposits.
Mesozoic deposits
Marine shale in Alaska
Permian deposits
Phosphoria Formation, Montana.
Devonian and Mississippian deposits
(resource estimates included for hachured areas only). Boundary dashed where concealed or where location is uncertain
0 200 400 600 MILES
0 200 MILES

Figure 5. Principal Reported Oil-Shale Deposits of the United States

TABLE 7. ASSAYS OF U.S. SHALE

State	Formation	Fischer Assay				
		Oil, wt %	Water, wt %	Spent Shale, wt %	Gas + Loss, wt %	Oil, GPT of Dry Shale
CO	Green River	13.7	1.1	82.0	3.0	35.9
IN	New Albany	3.1	0.8	94.8	1.3	7.8
MI	New Albany	4.0	0.8	94.0	1.2	10.0
KY	New Albany	5.2	0.9	92.0	1.9	13.3
TN	Chattanooga	3.7	0.7	93.2	2.4	9.5
IL	Coal Measures	4.0	4.2	90.0	1.8	10.4

Shale oil is defined as the liquid oil product recoverable from the thermal decomposition (pyrolysis) of kerogen, the organic material present in oil shale.

Crude shale oil is the liquid oil product recovered directly from the off-gas stream of an oil shale retort.

Synthetic crude oil (syncrude) is the upgraded oil product resulting from hydrogenating crude shale oil and later will be referred to as minimally-processed shale oil.

The term "retort" refers to the device or area in which the shale oil is liberated. For some processes, the retort is in the form of a mechanical system which includes shale rock handling equipment and a hot zone vessel. For other processes, the retort is in itself contained in the rubblized shale rock, referred to as an "in-situ retort."

Physical properties of various shale oils (not those used in this test program) derived from the Fischer Assay of Colorado oil shales ranging in grade from 10.5 to 75.0 gallons/ton are shown in Table 8. The properties of the oils obtained were rather uniform regardless of the grade of the raw shale. The chemical analyses of nine other shale oil products, derived from Fischer Assays of Colorado oil shale samples of various grades, are also similar as shown in Table 9; even though the grade of raw oil shale samples varied from 17.8 to 51.8 gallons/ton.

TABLE 8. PHYSICAL PROPERTIES OF SHALE OIL DERIVED FROM THE FISCHER ASSAY OF COLORADO OIL SHALE SAMPLES

Grade of Raw Oil Shale, gal/ton	10.5	26.7	36.3	57.1	61.8	75.0
Oil From Fischer Assay:						
wt % of Raw Shale	4.0	10.4	13.8	21.9	23.6	28.7
Specific Gravity at 60°/60° F	0.925	0.930	0.911	0.918	0.919	0.918
Kinematic Viscosity, 100° F, cSt	20.71	23.72	18.19	17.10	17.12	17.28
Gross Heating Value, BTU/lb	18,510	18,330	18,680	18,580	18,510	18,440
Pour Point, °F	80	75	85	80	80	75

Source: U.S. Bureau of Mines, 1951.

TABLE 9. CHEMICAL COMPOSITION OF SHALE OIL DERIVED FROM THE FISCHER ASSAY OF COLORADO OIL SHALE

Grade of Raw Oil Shale, gal/ton	17.8	18.8	19.5	21.4	22.3	29.8	36.6	38.0	51.8
Oil From Fischer Assay:									
Carbon, wt %	84.54	84.84	83.77	84.32	84.72	84.80	84.26	85.26	84.82
Hydrogen, wt %	11.32	11.38	11.17	11.40	11.72	11.60	11.76	11.76	11.68
Nitrogen, wt %	2.01	2.00	2.13	2.03	1.86	1.96	1.91	1.70	2.05
Sulfur, wt %	0.58	0.51	0.49	0.76	0.58	0.60	0.58	0.69	0.71
C/H Ratio	7.5	7.5	7.5	7.4	7.2	7.3	7.2	7.2	7.3

Source: U.S. Bureau of Mines, 1951.

Hundreds of U.S. patents have been issued concerning retorting of oil shale. Despite the number and types of retorting processes described in the literature, no one process has yet been shown to be best for all purposes.

Of the various types proposed, several of the most highly-developed retorting processes are:

- Indirect-heated types: Union Oil B; TOSCO II; Petrosix; USSR Kiviter and Galoter; Lurgi/Ruhrgas; Paraho Indirect
- Direct-heated types: Gas Combustion; Union Oil Company A, Paraho Direct

Direct-heated processes rely on internal combustion of fuel (generally recycle gas or residual carbon in spent shale) with air or oxygen within the bed of shale in the retort to provide all necessary process heat requirements. Products of combustion plus nitrogen (from air) accompany the off-gas stream from the retort.

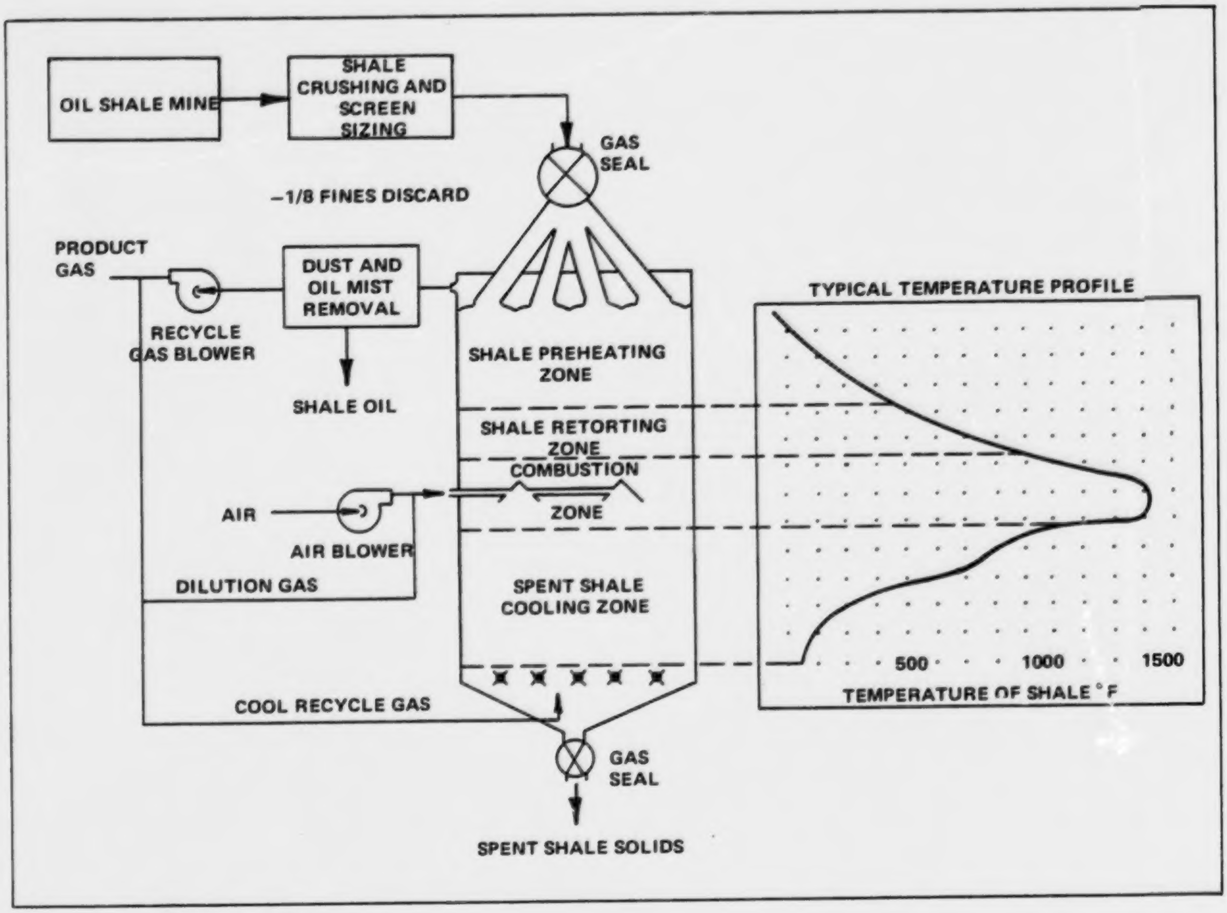
Indirect-heated processes utilize a separate furnace for heating solid or gaseous heat-carrier media which are injected, while hot, into the shale in the retort to provide process heat requirements.

Different retorts are developed and used to process oil shale of varying size, grade, and mineral content. Similarly, physical location, with respect to access, availability of water, and many other variables influences the use or optimization of any retort. In addition, the variation of parameters under which the pyrolysis of the kerogen is carried out affects the resulting oil quality. Carbon residue is generally left in the shale rock, and in most cases serves as fuel in support of the pyrolysis of the incoming raw oil shale. Many above-ground retorts utilize variations of a gas combustion process.

Figure 6 is a flowchart for the gas combustion process retorting of oil shale. The temperature chart shown on the drawing aids in understanding the process.

Relatively coarse fragments of oil shale may be fed to the vertical kiln retort for gas combustion retorting. While the optimum feed size has never been established, much work has been done on 0.25 to 3-inch shale.

Cold incoming oil shale feed enters the shale preheating zone, which is the upper portion of the retort. The shale solids become progressively warmer as they flow downward, due to direct heat exchange with hot gases rising from the retorting zone of the retort. Conversely, the countercurrent gas stream becomes cooled in passing upward through the bed of incoming shale. The bed depth in the preheating zone is sufficiently deep that the rising gas stream is cooled below the dewpoint of shale oil vapor (volatilized in the retorting zone); and the shale oil vapor condenses, forming a mist of minute oil droplets which is carried out of the top of the retort with the off-gas stream. These oil droplets are easily collectible in electrostatic precipitators.


OIL SHALE MINE
SHALE CRUSHING AND SCREEN SIZING
GAS SEAL
-1/8 FINES DISCARD
PRODUCT GAS
RECYCLE GAS BLOWER
DUST AND OIL MIST REMOVAL
SHALE OIL
SHALE PREHEATING ZONE
SHALE RETORTING ZONE
COMBUSTION ZONE
AIR
AIR BLOWER
DILUTION GAS
SPENT SHALE COOLING ZONE
COOL RECYCLE GAS
GAS SEAL
SPENT SHALE SOLIDS
TYPICAL TEMPERATURE PROFILE
500
1000
1500
TEMPERATURE OF SHALE °F

Source: Cameron Engineers, 1975.

Figure 6. Gas Combustion Retorting Process

In the retorting zone, organic matter in the shale is pyrolyzed or decomposed by heat. The hot gases rising from the combustion zone provide the necessary heat. As kerogen pyrolyzes, it yields oil (in vapor form), gas, and a residual carbonaceous product which adheres to the retorted shale solids. All vapors and gases are swept upward and leave the retort after passing through the shale solids as they descend into the combustion zone, the hottest zone in the retort. Oil vapors condense due to their being cooled by incoming feed shale, and the resulting oil mist leaves the retort with the off-gas stream.

In the combustion zone, a mixture of recycle gas and air is introduced. The available oxygen from the admitted air supports combustion of carbonaceous residue as well as combustibles in the recycle gas to produce hot flue gases. Shale solids reach their maximum temperature in the combustion zone. Hot flue gases rise and enter the pyrolysis zone.

Because of the good recovery of sensible heat from spent shale and from exit gas streams, it is necessary to add only about 400,000 BTU per ton of shale for all process heat requirements. This heat requirement may be met by combustion of carbonaceous residue which is present on the surface of shale particulate in the combustion zone, plus recycle gas which is injected with air into the combustion zone.

A stream of cool recycle gas is introduced at the bottom of the retort, and by heat exchange, serves the purpose of cooling hot spent shale solids as they descend.

Since above-ground or surface retorting of oil shale involves a large amount of excavation, shale rock handling and disposal of spent shale; in-situ retort processes have also been developed.

In situ retorting involves the in-place heating of an underground shale formation under conditions wherein the flows of heat, vapors, and liquids can be controlled, resulting in the recovery of acceptable quantities of gaseous and liquid products from the resource. Typical Green River formation oil shale occurs as hard, nonporous rock formations which are generally unsuitable for in situ retorting. It is therefore necessary to first modify the rock and create some degree of permeability. Discussions of in situ retorting often distinguish between "true" in situ processes, which involve only the drilling of wells, and "modified" in situ processes which require some mining in order to develop the underground retort rooms.

As mentioned previously, permeability of Green River oil shale is essentially zero. Oil shale is a fine-grained laminated rock consisting of a mixture of organic and inorganic minerals. The inorganic minerals, representing from 75 to 90 percent of the rock mass, are individual grains of nonspherical minerals whose equivalent diameters are less than 45 microns. Thus, if isolated, most individual grains would pass through a 325-mesh Tyler-series screen. The organic and inorganic matter are intimately bonded and cemented, forming the rock which is oil shale.

The porosity of the inorganic mineral matrix cannot be determined by methods used in determining porosity of conventional petroleum reservoir rocks because the organic matter is a solid material rather than a liquid. It is also insoluble in solvents. In certain zones, water-soluble minerals occur. These occurrences are as bedded zones, as vugs (i.e., small cavities in rocks), and as disseminated grains. These soluble minerals may be removed, resulting in some permeability of the remaining rock.

Shell Oil Company found that water-soluble minerals were mixed throughout much of the oil shale. This was found to be primarily nahcolite ($NaHCO_3$), and dawsonite $NaAl(OH)_2CO_3$. Shell recognized that these water-soluble minerals offer the possibility of developing porosity and permeability in the shale structure by leaching the shale with water.

Structural deformation occurs in rich oil shale as it is retorted under pressure. As samples of rich oil shale are retorted, they lose physical strength and collapse easily under pressure, with loss of permeability resulting.

The thermal conductivity of oil shale is very low, varying with shale grade and with temperature. A typical value for 25 gallons/ton shale at 1000°F is about 0.4 $BTU/hr/ft^2/ft/^\circ F$.

When oil shale is retorted, the organic material (kerogen) decomposes or pyrolyzes and yields a gas, an oil, and a residual carbon product. The retorted rock is different from the original shale. Residual carbon is deposited, and gas and oil vapor are removed. Retorted rock may have induced permeability due to the removal of mass. However, the structural properties of the rock have changed. Its yield stress value, its rate of compressive strain, its loss of mechanical strength, and the nature of deformation and their effects on permeability indicate that underground retorting can be seriously impaired by these changes in rock properties. Rich zones of shale are especially susceptible to collapse and loss of permeability during retorting.

"True in situ," or wellbore to wellbore retorting, is generally envisioned as a four-step process: (1) drilling a predetermined pattern of wells into the oil shale formation, (2) creating or increasing permeability by fracturing, leaching, or other means, (3) forcing hot fluids into the formation (which may be obtained by pumping compressed air and initiating combustion underground), and (4) recovering the oil created when solid kerogen reaches retorting temperatures. Heating may be achieved either by underground combustion or by forcing previously heated gases or liquids through the formation.

The "modified in situ" process for shale oil recovery consists of retorting a rubbled column of broken shale, formed by expansion of the oil shale into a previously mined-out void volume.

B. Background Information on Six Crude Shale Oils Obtained for Testing

Six crude shale oils were obtained through the cooperative efforts of EPA, SwRI, and SwRI-operated DOE-NASA Synthetic Fuels Center. Approximately 110 gallons of each of the six crude shale oils were obtained for use in this program, and are listed below in Table 10 by name and by SwRI Fuel code.

TABLE 10. SHALE OIL IDENTIFICATION

SwRI Code	Quantity Gallons	Crude Shale Oil Description	Date Received
EM-567-F	110	Paraho "SwRI," purchased	8/15/83
EM-568-F	110	Occidental, (FL-0313-L), Ref 79-149	8/24/83
EM-569-F	110	Superior, (FL-0318-L), ERDA	8/24/83
EM-570-F	120	Paraho "DOE," (FL-0314-L), (SOA-76-A)	8/24/83
EM-571-F	110	Geokinetics/Four Corners	9/07/83
EM-573-F	110	Union	12/06/83

1. Paraho

Two samples of Paraho crude shale oil were obtained for use in this program. The Paraho "SwRI" (EM-567-F) material was purchased from Paraho Development Corp. in September 1983. Through Ms. Deborah O'Connor of Paraho Development Corp., it was verified that the shale oil received was processed through the "Paraho Pilot Plant" located near Rifle, Colorado, using the direct-fired mode of operation. (Paraho's Pilot Plant is an above-ground retort and was moved from Anvil Points to Rifle, Colorado 1982-1983). This plant has been used to process raw shale from various locations around the world. She confirmed that we did receive a "crude" product in that no hydrotreating was performed, and that the shale oil was of recent vintage (1983).

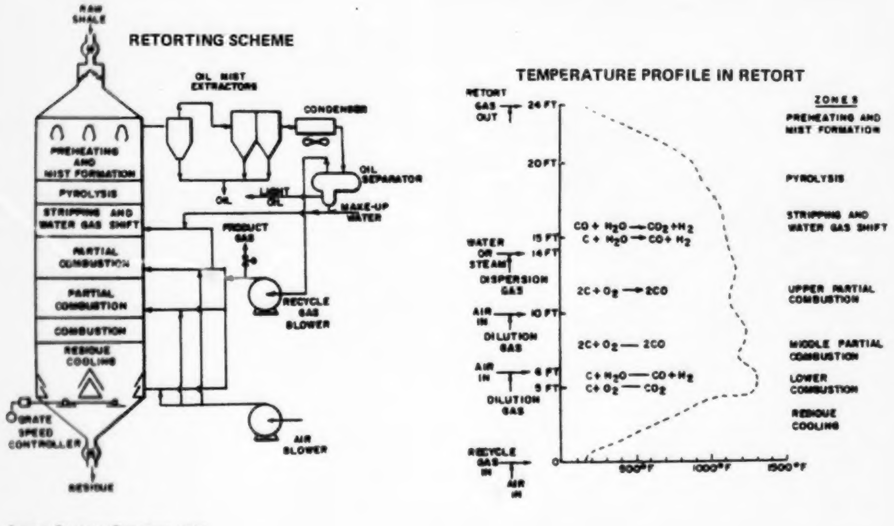
The other Paraho product, Paraho "DOE" (EM-570-F), was obtained from U.S. Government storage as Laramie, Wyoming. Background on this product was obtained from Mr. Ed Smith of the University of Wyoming Research Corporation. According to Mr. Smith, the oil shale rock came from the Green River Formation at Anvil Points River, Rifle, Colorado, and was processed in the Paraho Pilot Plant using the direct-fired mode in late 1975 or early 1976. No upgrading of the shale oil was performed; although he commented that as part of the normal handling, the shale oil vapors and mist, along with water vapor from combustion, are condensed and sent to a holding tank with a temperature of 150 to 200°F. The product was taken from this tank, intentionally leaving most of the water and sediment behind.

A consortium of 17 companies, known as the Paraho Oil Shale Project, was formed, and activities at Anvil Points Oil Shale Mine and Retorting Facility, Rifle, Colorado were initiated in late 1973. A 4.5-foot diameter pilot kiln was built, followed by a 8.6-foot inside diameter semi-works retort with a nominal capacity of 450 tons/day. This latter retort has been operated in both a direct mode and indirect mode since 1974, producing 10,000 barrels of shale oil for the Navy in a 56-day continuous run in March 1975.

As a result of the successful demonstration program, the U.S. Department of Defense and Department of Energy awarded Paraho a number of production contracts to produce and ship up to 100,000 barrels of crude shale oil. Production was carried out at the Anvil Points facility from 1976 to 1978. A 105-day continuous on-stream operation and oil yields above 96 percent were obtained. The crude shale oil produced has been commercially refined into military products.(13)

The above-ground gas combustion retort utilized a vertical vessel fed from the top with raw shale, which moved downward by gravity through a top preheat zone, thence into a retorting zone, next into a combustion zone, and finally into a spent shale cooling zone. Oil vapors from the retorting zone passed upward through the preheat zone, where they condensed to a stable aerosol mist that passed out with the retort gases and were recovered in mist collectors.

The Paraho retort can be operated in either the direct- or indirect-heated mode. Figure 7 illustrates the Paraho retort in the direct mode, and a temperature profile in the retort is also given.

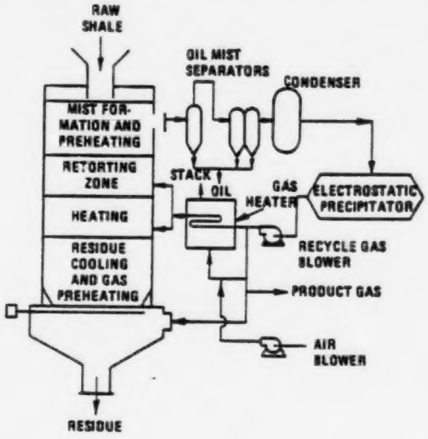

RETORTING SCHEME
RAW SHALE
OIL MIST EXTRACTORS
CONDENSER
OIL SEPARATOR
OIL
LIGHT OIL
MAKE-UP WATER
PREHEATING AND MIST FORMATION
PYROLYSIS
STRIPPING AND WATER GAS SHIFT
PARTIAL COMBUSTION
PARTIAL COMBUSTION
COMBUSTION
RESIDUE COOLING
PRODUCT GAS
RECYCLE GAS BLOWER
AIR BLOWER
GRATE SPEED CONTROLLER
RESIDUE
TEMPERATURE PROFILE IN RETORT
RETORT GAS OUT
24 FT
20 FT
15 FT
14 FT
10 FT
6 FT
5 FT
0
WATER OR STEAM
DISPERSION GAS
AIR IN
DILUTION GAS
AIR IN
DILUTION GAS
RECYCLE GAS IN
AIR IN
CO + H2O → CO2 + H2
C + H2O → CO + H2
2C + O2 → 2CO
2C + O2 — 2CO
C + H2O — CO + H2
C + O2 — CO2
500°F
1000°F
1500°F
ZONES
PREHEATING AND MIST FORMATION
PYROLYSIS
STRIPPING AND WATER GAS SHIFT
UPPER PARTIAL COMBUSTION
MIDDLE PARTIAL COMBUSTION
LOWER COMBUSTION
RESIDUE COOLING

Source: Cameron Engineers, 1975

Figure 7. Paraho-Retort-Direct Mode

In the direct operating mode, retort off-gases (approximately 100 BTU/SCF) are recycled to the retort at three points. These gases, together with combustion of a portion of the carbonaceous residue on the spent shale, provide the heat for the process. The spent shale, with a 2-percent carbonaceous coating, is discharged to disposal at approximately 150°C (300°F). Retort gases, oil mist, and vapors leave the top of the retort at approximately 66°C (150°F), and pass through a cyclone, wet electrostatic precipitator, and air condenser to remove oil. A portion of these gases is recycled to the retort.

The Paraho process may also be operated in the indirect mode (Figure 8) in which case no combustion is carried out in the retort per se. The retort gases therefore have high heating value (900 BTU/SCF). A portion of these gases is used to heat a second portion of these gases in an external furnace, and the latter is recycled to the retort as its heat source. The spent shale has a carbon content of 4.5 percent. A combination of direct and indirect operating modes may also be employed.


RAW SHALE
OIL MIST SEPARATORS
CONDENSER
MIST FORMATION AND PREHEATING
RETORTING ZONE
HEATING
RESIDUE COOLING AND GAS PREHEATING
STACK
OIL
GAS HEATER
ELECTROSTATIC PRECIPITATOR
RECYCLE GAS BLOWER
PRODUCT GAS
AIR BLOWER
RESIDUE

Source: TRW, 1976.

Figure 8. Paraho-Retort-Indirect Mode

Since the Paraho retort can be operated in either the indirect or the direct heat mode, the mode of operation should be specified. The major observable difference in product quality between direct and indirect retort operation is in the pour point and viscosity. Table 11 illustrates this fact.

TABLE 11. PARAHO RETORTING (PRODUCT OIL QUALITY)

	Direct Heated	Indirect Mode
Gravity, °API	21.4	21.7
Viscosity, SUS, AT 130°F	90	68
Viscosity, SUS at 210°F	46	42
Pour Point, °F	85	65
Ramsbottom Carbon, wt %	1.7	1.3
Water Content, vol %	1.5	1.4
Solids, B.S., wt %	0.5	0.6

Source: Cameron Engineers, 1975

The shale oil product may be upgraded by conventional hydrotreatment to remove nitrogen and sulfur, and refined to normal petroleum products.

2. Superior

The Superior (EM-569-F) material, or shale oil product, was also obtained from the Laramie Energy Technology Center, Laramie, Wyoming. The Superior crude was produced using a "circular grate" above-ground retort utilizing indirect heating mode.

Superior Oil has owned some 6500 acres of oil shale land in the northern Piceance Creek Basin for nearly 40 years. In 1967, it began a drilling and geological evaluation program, and found that the deeper oil shales on the property contained attractive quantities of nahcolite, naturally occurring sodium bicarbonate ($NaHCO_3$). The oil shale also contained significant quantities of dawsonite, which can be decomposed to yield aluminum oxide (Al_2O_3) and soda ash (Na_2CO_3). A research program was therefore initiated to permit integrated recovery of these saline minerals and shale oil, resulting in development of a circular grate retort, as illustrated in Figures 9 and 10.

The doughnut-shaped retort has five separately divided sections, through which the shale travels in sequence. These sections are a loading zone, retorting zone, residual carbon recovery zone, cooling zone, and unloading zone. Hot gases are drawn downward through the bed of shale on the grate in the retorting zone, producing oil-laden vapors which are removed and the shale oil condensed. The oil-denuded and cooled gases are next recycled to the cooling zone, and drawn downward through the spent shale to reduce its temperature prior to discharge. The cooled shale is fed to the leaching plant for recovery of alumina and soda ash.

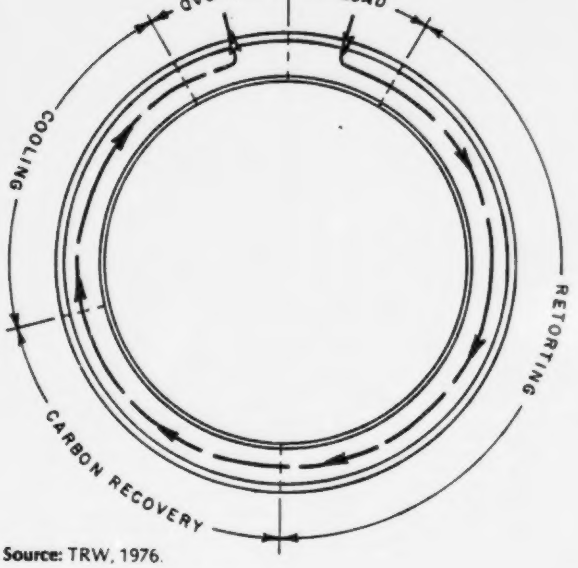
During retorting, the dawsonite in the retorted shale is converted to alumina and sodium carbonate. These are recovered in the leaching plant by treatment with caustic solution, followed by carbonation to produce $NaHCO_3$, and calcination to convert $Al(OH)_3$ to cell-grade alumina.

The spent shale (sodium minerals and shale oil denuded) is returned to the underground mine as a wet cake on the flip side of a production conveyor.

3. Union

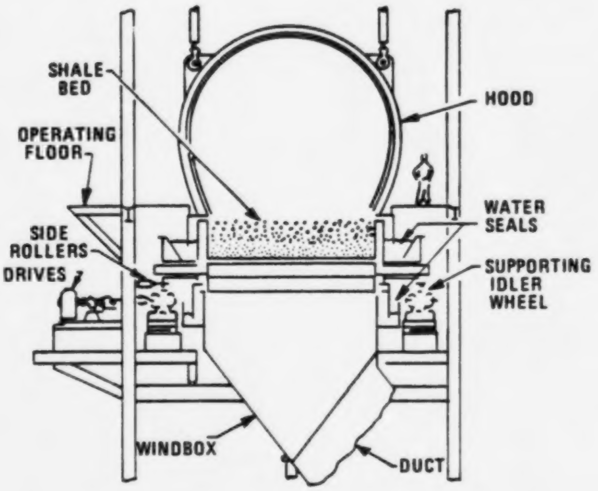
The Union (EM-573-F) crude shale oil was provided by Union Oil Company through EPA, for use in this program. Background information for this material was obtained through Mr. John H. Duir of Union Oil Company.

According to Mr. Duir, the Union shale oil originated from oil shale rock produced in Union's mine near Parachute, Colorado, and was processed in an above-ground retort using the "Unishale-B" process. The shale oil we have is a pilot plant sample product generated in late 1983. The Unishale-B process is an indirect-heated process. The crude shale oil we received was not intentionally de-ashed, although some settling was unavoidable. It had not been


UNLOAD
LOAD
COOLING
RETORTING
CARBON RECOVERY

Source: TRW, 1976.

Figure 9. Plan view of circular grate retort showing movement of charge through various zones


SHALE BED
HOOD
OPERATING FLOOR
WATER SEALS
SIDE ROLLERS
DRIVES
SUPPORTING IDLER WHEEL
WINDBOX
DUCT

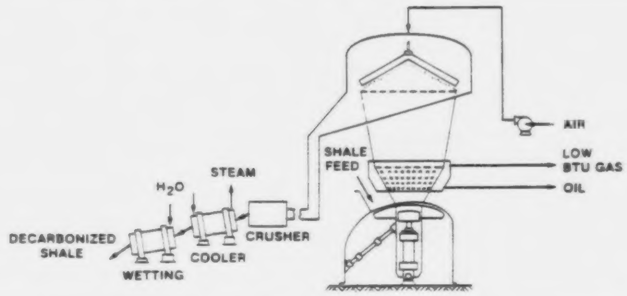
Source: TRW, 1976.

Figure 10. Cross section of circular grate retort

de-arsenated (arsenic level reduced). Mr. Duir mentioned that shale oil is apt to polymerize, and that degradation of the crude shale oil never stops due to the high content of reactive olefinic and heterocyclic materials. More detailed information concerning Union retorts was obtained from reference 15, provided by Mr. Duir.

Union Oil has been involved in the development of surface oil shale retorting for close to 40 years and has pioneered the development of solids upflow retorting.

All of Union's retorting technology utilizes the upflow of solids. To accomplish this, the solids are pumped upward through an expanding cone. The first retorting concept, Retort A, is shown in Figure 11. A reciprocating piston, totally immersed in relatively cold product oil, is used to move the shale. As the solids are pumped upwards through the expanding conical retort shell, an overflowing cone of retorted shale is formed above the top edge of the retort.



Source: Union Oil, Ref. 15

Figure 11. Retort A

The shale is heated by a once-through stream of air. Heat is supplied by burning the carbonaceous deposit on the retorted shale in the upper part of the retort. The hot flue gases heat the raw shale to temperatures necessary for retorting. As the gases cool, the oil condenses and is withdrawn from the cold disengaging section of the retort as a liquid. Noncondensible gases are sent to further processing for heavy ends and hydrogen sulfide removal.

The countercurrent stream of hot gas heats the rising bed of oil shale to the necessary retorting temperature. Several very important process advantages are obtained by using solids upflow and retorting gas downflow.

Kerogen in the oil shale is decomposed on retorting and is liberated from the rock as oil and gas vapors. Retorting products are quickly forced downward by the educting gas towards the cooler shale in the lower portions of the retort, rapidly quenching the polymerization reactions which, if allowed to continue, would form heavy oil that is difficult to refine. As the oil is condensed on the bed of cooler incoming shale, gravity assists its drainage away from the retorting zone eliminating potential agglomeration within the retort bed caused by refluxing and coking of the product oil.

Union carried the Retort A concept through 2 ton/d and 50 ton/d pilot operations and then through a demonstration plant stage. The demonstration plant, built in the late 50s in Parachute Creek Valley, processed up to 1,200 ton/d and produced about 800 bbl (127 m^3)/d of shale oil.

To improve product yields and quality, the Unishale B Retorting Process was developed. Retorting is accomplished by indirect heating utilizing a recycle product gas heated in a fired heater to 950-1000°F (510-540°C). Both fixed-bed and continuous pilot-plant operations give high yields of liquid product, essentially equal to Fischer assay values. The retort product gas has a high heating value, above 800 BTU/SCF (30 MJ/m^3). Product quality from the low temperature, low residence time, and oxygen free retorting is excellent, and the discarded retorted shale contains a nominal 4 wt % carbonaceous deposit.

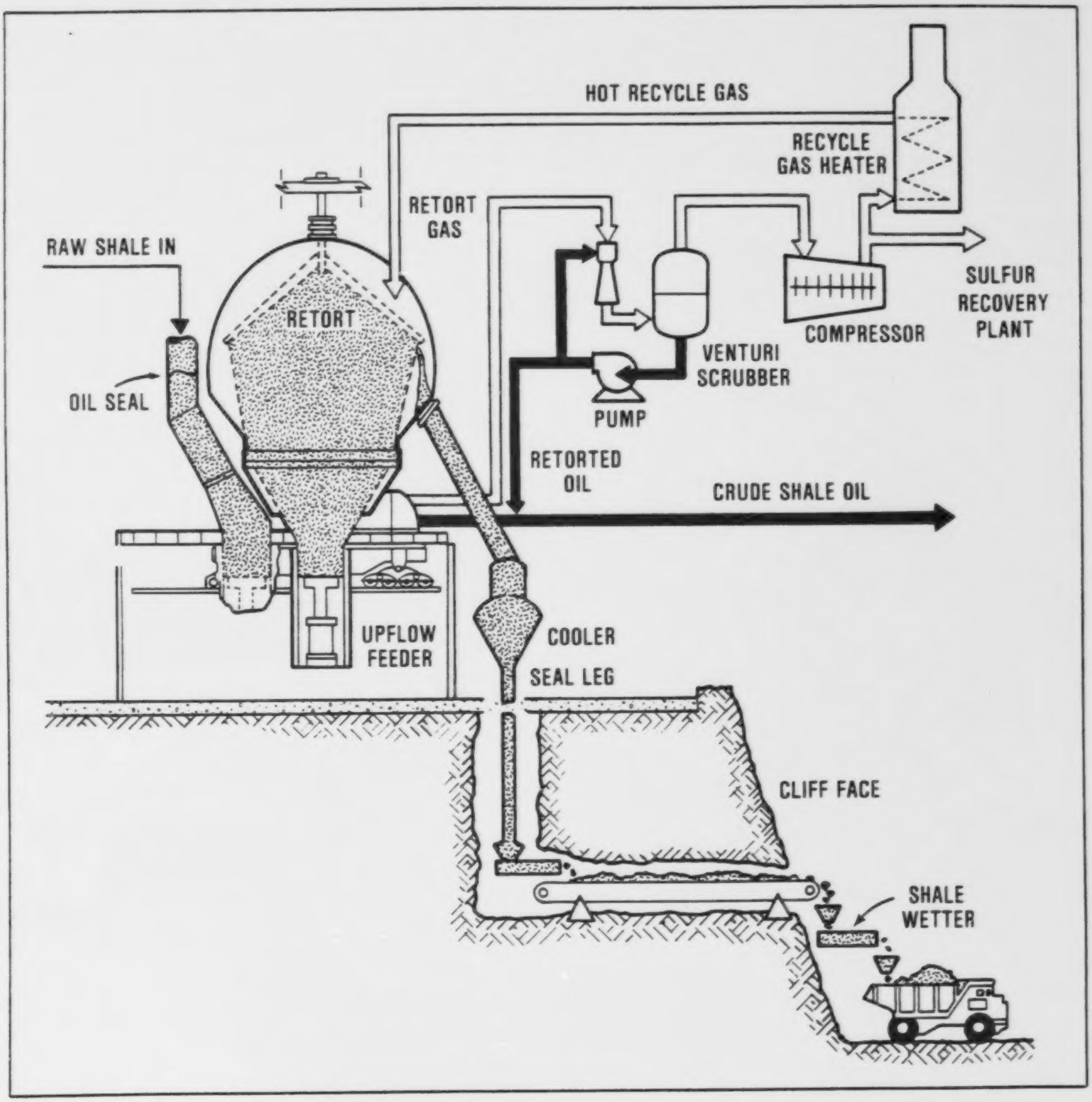
Figure 12 illustrates the construction of the Unishale B surface retort. Raw shale, obtained from room and pillar mining of the rich Mahogany zone of the Parachute Creek section of the Green River geologic formation, is crushed to less than 2 inch pieces. Crushed shale enters the solids feeder underneath the retort where a 10-ft (3-m) diameter piston will force the shale upward into the retort. Shale oil product acts as a hydraulic seal in the feed chute to maintain the retort pressure.

As the oil shale rises through the retort cone, it is contacted by a countercurrent flow of hot recycle gas entering the top of the retort dome. The hot recycle gas provides the heat required for the retorting process. The oil shale kerogen decomposes into liquid and gaseous organic products which diffuse from the shale particles leaving behind a solid carbonaceous deposit on the retorted material. The bulk of the liquid product trickles down through the cool incoming shale, and the balance, in the form of mist, is carried from the retort by the cooled gases.

The gas and liquid are separated from the shale in the slotted wall section comprising part of the lower shell cone. A disengaging section surrounds the lower cone. The liquid level in this section is controlled by withdrawing oil product. Shale particles which fall through the slots into the disengaging section are recycled by screw conveyors into the feed chute. Very fine shale particles which may collect at the bottom of the feeder case are pumped in an oil slurry back to the retort by way of the disengaging section.

Retorted shale is forced up and over the edge of the retort cone and falls by gravity down chutes through the retort dome wall at the retorted shale outlets. The hot retorted shale continues to pass by gravity through a cooling vessel where it is cooled by a water spray. Steam generated in the quenching and cooling operation also strips retort gases from the pores of the retorted shale. It is condensed and returned to the cooling vessel.

Dry, cooled retorted shale leaves the cooling vessel and passes through a pressure-letdown seal leg. Steam passes through the leg of shale at a rate sufficient to drop the pressure from retort conditions to atmospheric. The retorted shale is then moved by conveyor belt to an enclosed chute which


HOT RECYCLE GAS
RECYCLE GAS HEATER
RETORT GAS
RAW SHALE IN
RETORT
OIL SEAL
VENTURI SCRUBBER
COMPRESSOR
SULFUR RECOVERY PLANT
PUMP
RETORTED OIL
CRUDE SHALE OIL
UPFLOW FEEDER
COOLER
SEAL LEG
CLIFF FACE
SHALE WETTER

Source: Union Oil, Ref. 15

Figure 12. Unishale B

transports it to the canyon floor. It will be wetted, spread, compacted, contoured, and vegetated with native plants.

Properties of the full-range liquid product from the retort are given in Table 12. Solids upflow retorting combined with an oxygen-free recycle gas gives a product oil having a moderately low pour point and a low Conradson carbon residue.

Union's past research work demonstrated that carbonaceous deposits on retorted shale could be completely reacted to produce a usable hydrogen-rich gas or to supply heat for process use. Development of a retorted shale combustion process, compatible with the Unishale B Retort is planned. This additional processing would raise the current 70 percent thermal efficiency of the Unishale B process to 83 percent.

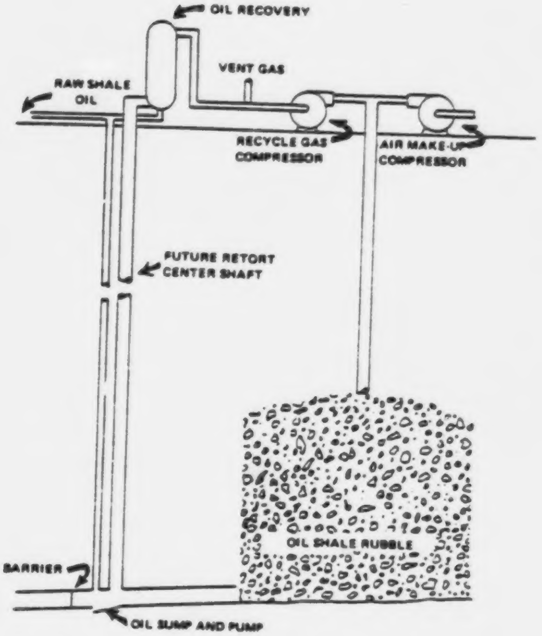
TABLE 12. PROPERTIES OF CRUDE SHALE OIL UNISHALE B RETORT(15)

Gravity, °API	22.2
ASTM, D-1160 Distillation, °F	
IBP	150
10	390
30	620
50	770
70	875
90	1010
Max	1095
Sulfur, wt %	0.8
Nitrogen, wt %	1.8
Oxygen, wt %	0.9
Fischer water, wt %	0.2
Pour Point, °F	60
Arsenic, ppm	50
Conradson Carbon Residue, wt %	2.1
Heating Value, Gross M BTU/gal	142

4. Occidental

Mr. Smith also supplied some information on the Occidental (EM-568-F) crude shale oil, which was also obtained from U.S. Government storage. The Occidental crude was produced from an in situ retort known as Retort No. 6. This in situ retort used the "Vertical Modified In-Site" (VMI) process. No hydrotreating was performed, but Mr. Smith thought that the crude was probably processed through an electrostatic de-salting process, developed for processing petroleum crudes, and then heat-settled to remove water and sediment. The Occidental product was probably processed in 1979, based on its inventory code number.

From Reference 12 and 13, the Occidental process involves three basic steps. The first step is the mining out of approximately 15 to 20 percent of the oil shale deposits (preferably low-grade shale or barren rock), either at the upper and/or lower level of the shale layer. This is followed by drilling vertical longholes from the mined-out room into the shale layer, and loading those holes with an ammonium nitrate-fuel oil (ANFO) explosive. The explosive is then detonated with appropriate time delays so that the broken shale will fill both the volume of the room and the volume of the shale column before blasting. Finally, connections are made to both the top and bottom, and retorting is carried out (Figure 13). Retorting is initiated by heating the top of the rubbled shale column with the flame formed from compressed air and an external heat source, such as propane or natural gas. After several hours, the external heat source is turned off, and the compressed air flow is maintained, utilizing the carbonaceous residue in the retorted shale as fuel to sustain combustion. In this vertical retorting process, the hot gases from the combustion zone move downward to pyrolyze the kerogen in the shale below that zone, producing gases, water vapor, and shale oil mist which condense in the trenches at the bottom of the rubbled column. The crude shale oil and byproduct water are collected in a sump and pumped to storage. The off-gas consists of products from shale pyrolysis, carbon dioxide, and water vapor from the combustion of carbonaceous residue, and carbon dioxide from the decomposition of inorganic carbonate (primarily dolomite and calcite). Part of this off-gas is recirculated to control both the oxygen level in the incoming air and the retorting temperature.



Source: TRW, 1976

Figure 13. Retorting operation of the Occidental modified in situ process

From Reference 14, Occidental Petroleum Corporation entered into an agreement with D.A. Shale, Inc. in mid-1972 and acquired about 4,000 acres of land between Roan and Parachute Creeks, Garfield County, Colorado. The 2400 shale-bearing acres contain an estimated shale oil reserve of 0.3 billion barrels, averaging about 17 gallons of oil per ton of shale.

Site preparation began in 1972 and construction of the first modified in situ retort, 1E, was completed by December 1972. Retort 1E contained approximately 4000 tons of broken shale at 25 percent average void volume and was ignited in June 1973. Since then, operations have been underway almost continuously, through a series of progressively larger retorts. Retort 6 has 100 times the volume of the first experimental unit and does not require further scale-up for commercial operations.

The initial three retorts were located off a single horizontal opening. Retort 1E was mined in the form of a small room with a vertical cylindrical rise providing the initial void volume. The retort operated successfully, producing over 1200 barrels of oil. In Retort 2E, the void volume was reduced, the blast pattern modified, and the retort depth increased 22 feet, the retort was fired in March 1974. Retort 3E tested an entirely different retort design which ultimately provided the basis for scale-up to commercial-size units. Retort 3E was ignited in February 1975 and produced 1600 barrels of oil. Following completion of the first three retorts, operations were transferred to a new large-scale development mine. Retort 4 was the first commercially-sized unit, being 50 times larger than the first retorts. Ignited in 1975, Retort 4 produced some 27,500 barrels of oil, somewhat less than the full potential, with difficulties traced to geologic conditions resulting in inadequate ore rubblization. Geologic conditions were overcome in Retort 5 by design changes. However, the method of rubblization using a vertical "tapered-slot" void, produced an uneven horizontal distribution of porosity resulting in channeling of gas flow. Burned in 1977, Retort 5 produced 10,100 barrels of oil. Retort 6 was a scale-up of the successful retort 3E design, was half an acre in cross-sectional area, and high as a 30-story building. The 24 percent void volume in the retort was created by mining horizontal rooms to provide more uniform permeability in the rubble zone. Retort 6 was ignited in August 1978, and operating conditions were upset soon after start-up by a partial collapse of the retort roof (sill pillar slumping into the retort). However, corrective actions were taken and 55,700 barrels of oil were produced from this retort, representing 46 percent of the oil in place.

Retorts 7 and 8, currently under construction, will utilize the Retort 6, three-level design, except that they will be operated from the ground surface rather than from a mine level separated from the retort by a sill pillar. Retorts 7 and 8 will be operated simultaneously to study conditions resulting from multi-retort operation.

OCCIDENTAL MODIFIED IN SITU RETORTING EXPERIMENTS

Retort	Year Production	Size (feet)	Oil Produced (barrel)
1E	1973	31 x 31 x 72	1200
2E	1974	32 x 32 x 94	1400
3E	1975	32 x 32 x 113	1600
4	1975	120 x 120 x 271	27,500
5	1977	118 x 118 x 158	10,100
6	1978	162 x 162 x 254	55,700
7	1982	162 x 162 x 243	97,000 (est.)
8	1982	162 x 162 x 242	97,000 (est.)

The D.A. Shale property is at best only marginal for sustained commercial production. Occidental bid unsuccessfully for Prototype Oil Shale Leases C-a and U-a. Occidental has since acquired a major interest in the Federal C-b Oil Shale Tract from the original leases, and has limited commercial plans to that tract.

5. Geokinetics

Information on the Geokinetics material (EM-571-F) was provided by Mr. Eddie French of the SFSC-AF. This shale oil likely came from an in situ retort operated near Vernal, Utah (within 70 miles). The crude product was produced in the 1982-83 time period, using a modified in situ process labeled "LOFRECO", representing "Low Front-End Cost."

From Reference 14, Geokinetics, Inc. was organized in April 1969, as a minerals development company. In July 1972 Geokinetics organized a joint venture with a group of independent oil companies to develop in situ methods of shale oil extraction, and to acquire and develop oil shale leases. Work on the horizontal modified in situ process began in 1972. Design and cost estimates were made for a horizontal modified in situ operation on Tracts C-b, U-a and U-b, in preparation for bidding on the prototype Federal Oil Shale lease sale. Small-scale pilot tests in steel retorts, to simulate a horizontal basis, were carried out in 1974 and early 1975. In April 1975 in situ field tests began in Kamp Kerogen, and have continued without interruption to date.

During 1975 and 1976 the basic parameters of the process were estimated. In late 1976, a cooperative agreement was signed with DOE, with whose assistance progress was greatly accelerated. In 1977 and 1978 the process was scaled up substantially, and rock breaking designs were improved and tested. In 1979 larger retorts were tested, up to one-quarter of full scale, and tests began to optimize recovery. The first full-sized retort was blasted in 1979. During 1980 a second full-sized retort was blasted, and equipment was installed for ignition of the first full-sized retort. Twenty-four experimental retorts have been blasted, 14 retorts have been burned, and 15,000 bbls of oil produced. Geokinetics expects to complete its R&D program in 1982, and begin immediately to design and construct a 2000 BPD commercial production unit. Thirty-thousand acres of oil shale leases were acquired between 1975 and 1980, representing in-place reserves of 1.7 billion barrels of shale oil.

Geokinetics is developing the horizontal in situ retort, explosive fracturing of the oil shale. There are three basic applications of the process:

a. The LOFRECO process, where blast holes are drilled from the surface to fracture the oil shale bed.

b. Horizontal modified in situ, where part of the bed is mined out to provide expansion space for the broken rock.

c. Secondary recovery after room-and-pillar mining. After mining is completed, the pillars, roof and floor are blasted to create a large volume of rubblized rock that is retorted using the horizontal in situ process.

In the LOFRECO Process, a pattern of blast holes is drilled from the surface through the overburden and into the oil shale bed. The explosion produces an upward movement of the overburden and fragments of oil shale. The bottom of the retort is sloped to provide for drainage of the oil to the production wells. Air injection holes are drilled at one end of the retort, and gas exhaust holes are drilled at the other end. The oil shale is ignited at the air injection holes, and air is injected to establish and maintain a burning front. The front is moved in a horizontal direction through the fragmented shale toward the gas exhaust holes at the far end of the retort. The burning front heats the oil shale ahead of the front driving out the oil, which drains to the bottom of the retort, and flows along the sloping bottom to a sump, where it is lifted to the surface by conventional oil field pumps. As the burning front moves from the air injection to the gas exhaust holes, it burns residual coke in the retorted shale as fuel, and produces a large volume of low BTU combustible gas.

C. Properties of the Six Crude Shale Oils

In order to select three candidate crude shale oils to be introduced to the IH DT-466B in this program, various properties of the six crude shale oils had to be established. Since all shale oils were received in the crude form, it was assumed that they contained water and sediments which would have to be separated out before attempting to use them in the test engine. Heating and settling was one method proposed in which the crude is warmed and allowed to stand for a number of days, but this would have entailed discarding up to as much as one-third of the contents of the drums and it was assumed that most of the crudes came from some type of holding tank in which most of the water and sediment were left behind. Since the crude had to be filtered for use by the engine, it was decided that the crude would be filtered prior to selection of the candidate crudes for use in the engine. Table 13 lists a number of analyses proposed in order to characterize the properties of both the "as received" and "filtered" crude shale oils. Of the analyses listed, FIA, heat of combustion, particulate, cetane number, and friction and wear were not performed.

Some of the crude shale oils approached the consistency of a "black mayonnaise" or solids at temperatures near 70°F. In order to obtain representative samples of each of the "as received" crudes, the individual drums were heated to near 150°F, mixed for about 1 hour with an air-powered stirrer as shown in Figure 14, and pumped to clean storage drums. Samples for analysis were taken midway in the drum transfer process.

Due to the tight mechanical clearances present in the engine's fuel injection system, the crude material had to be filtered before introduction to the engine. For research purposes, filtration system consisting of a series of progressively finer spin-on filters was chosen for filtration of the relatively small quantities (2-55 gallon drums of each) of the individual crude shale oils. The odor from the shale oils was rather pungent and strong so filtration was carried out under a ventilation hood (shown in Figure 15) which also enclosed the test engine. An oil-absorbent gravel was used in the fuel handling and engine test areas to facilitate clean-up of any shale oil spillage.

A schematic of the filtration system is given in Figure 16. This system was enclosed in a fabricated oven, Figure 17, containing heater elements to maintain the temperature of the shale oils at 150 to 200°F during filtration. A gear pump was used to pressurize the system to approximately 60 psig. At these conditions, a 55 gallon drum of shale oil was filtered in about 2-3 hours. It should be noted that the last two filters of the system utilized the same elements normally used on the DT-466B test engine. Filtered shale oil samples were taken from the downstream end of the system about midway through processing time of each shale oil.

Samples of "raw" (or "as received") and samples of "filtered" crude shale oils were submitted for analyses. Resulting properties of these materials are given in Table 14. For comparative purposes, the properties of DF-2 (EM-528-F) used in establishing baseline performance and emission levels are given in Table 15. Viscosities of the shale oils were determined at 120 and 210°F. Using the ASTM Standard Viscosity-Temperature Chart for Liquid Petroleum Products (Chart D), a straight-line relationship was assumed and plotted in Figure 18.

To obtain boiling point distribution data on these samples, the "Proposed Test Method for Boiling Point Distribution by Gas Chromatography"(17) was used. This procedure entailed performing a boiling point distribution of the shale oil with an internal standard, then repeating the process on the same shale oil without the internal standard. Through computer software, the internal standard was quantified and hence a quantitative boiling point distribution determined. Figure 19 shows the boiling point distribution (determined by the modified ASTM D2877 procedure) of the shale oil crudes along with that given for the DF-2 (based on the standard ASTM D86 procedure). Generally, the

TABLE 13. PROPOSED CHARACTERIZATION OF SHALE OIL CRUDE

Test	ASTM Procedure	Analysis Proposed for Samples	
		As-Received	After Filtration
API Gravity	D287[a]	all 6	all 6
Viscosity	D445[b]	all 6	all 6
Boiling Pt. Dist.	D2887	all 6	all 6
Flash Point	D93	--	--
Pour Point	D97	all 6	all 6
F.I.A.	D1319	--	"too dark"
Heat of Combustion	D240	--	c
Ash	D482	all 6	all 6
Particulates	D2276[d]	--	c
Water & Sediment	D1796[e]	all 6	all 6
Carbon Residue	D524	all 6	all 6
Cetane Number	D613[f]	--	c
Carbon/Hydrogen	D1378	all 6	all 6
Nitrogen	g	1	c
Oxygen	h	1	c
Sulfur & Elements	XRF[i]	1	c
Elements	AA[j]	--	--
Friction & Wear	D2714	--	c

---

[a] heat to minimum temp. for fluidity

[b] viscosity at 122, 210 and 300°F

[c] only those most likely to be submitted for engine test

[d] possible modification of procedure - dilute sample and use 8 m filter media

[e] sample must be soluble in toluene

[f] at 300°F

[g] determined by pyrochemiluminescence

[h] determined by Centichem (commercial lab)

[i] to be determined by using x-ray fluorescence

[j] using Atomic Absorption, analysis for various metals would be dependent on results obtained from XRF

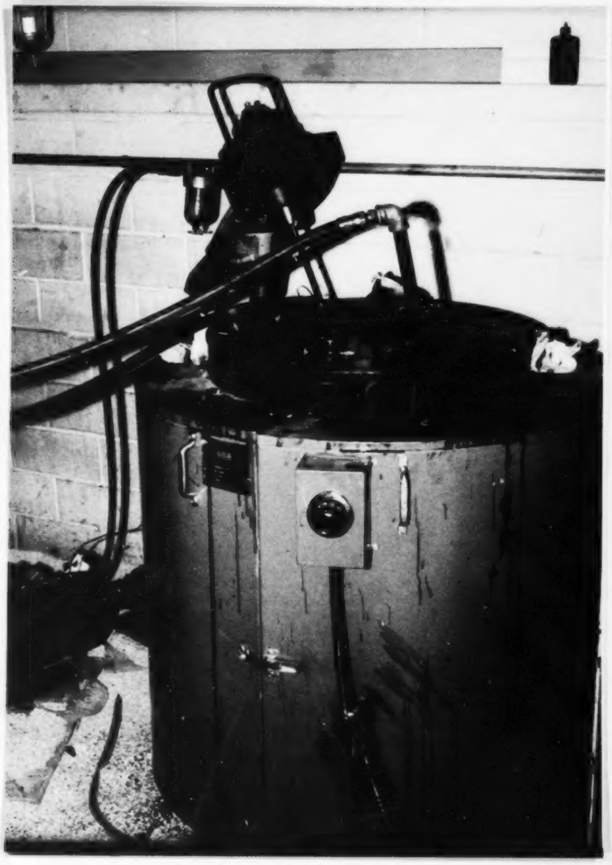
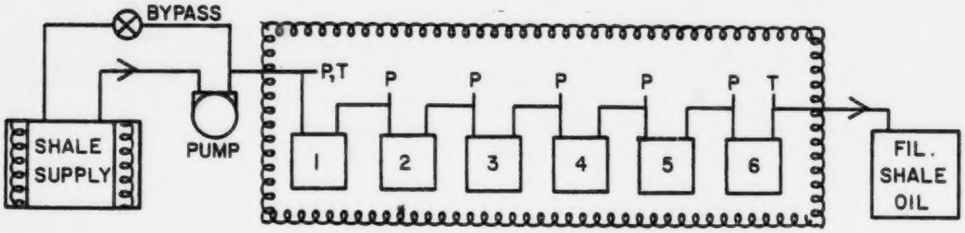


Figure 14. 55-gallon drum heater used to warm the shale oil prior to pumping

Figure 15. Ventilation hood used during shale oil handling and filtration


BYPASS
PUMP
SHALE SUPPLY
P,T
P
P
P
P
P
T
1
2
3
4
5
6
FIL. SHALE OIL

Filter Identification

1. Fleetguard LF 670 (40 μm)
2. Fleetguard FF 213 (18 μm)
3. Fleetguard FS 1216 (18 μm & water separator)
4. Fleetguard LF 777 (10 μm)
5. Fleetguard FF 5019 (2 μm) (DT-466B primary filter - IH regards 85 μm)(16)
6. Fleetguard FF 5020 (1 μm) (DT-466B secondary filter - IH regards as >4 μm)(16)

Figure 16. Schematic of filtration system

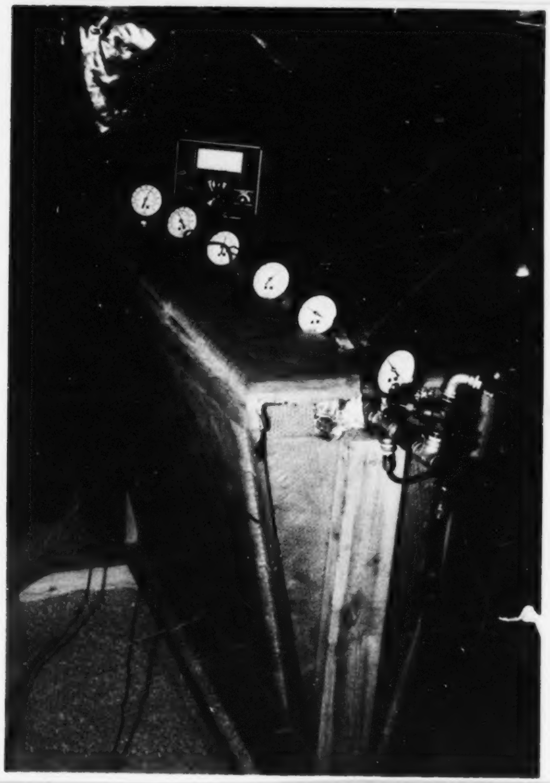


Figure 17. Filtration system enclosed in a fabricated oven

TABLE 14. PROPERTIES OF CRUDE SHALE OLS, "RAW" AMD "FILTERED"

Origin	Fuel Code Number	Crude State	API Gravity	Sp. Grav.[a] at 75°F	Pour Pt., °F	Temp. for 3 centi-stokes, °F	Water %	Sediment %	Ash %	Carbon Residue, %	H/C Ratio
Paraho	EM-567-F	Raw	20.7	0.9241	80	245	5.3	0.15	0.082	1.88	1.619
SwRI	EM-582-F	Filtered	20.8	0.9235	85	245	0.6	<0.05	0.017	1.79	1.620
Occidental	EM-568-F	Raw	22.9	0.9110	56	255	7.0[c]	0.05	0.051	0.91	1.683
	EM-583-F	Filtered	23.5	0.9074	65	253	2.4[c]	<0.05	0.020	0..91	1.682
Superior	EM-569-F	Raw	17.9	0.9414	87	307	1.0[d]	0.10	0.045	3.24	1.571
	EM-584-F	Filtered	18.5	0.9376	90	327	0.5[d]	<0.05	0.026	3.12	1.580
Paraho	EM-570-F	Raw	18.7	0.9364	81	283	1.2	0.2	0.067	2.45	1.631
DOE	EM-585-F	Filtered	19.5	0.9315	85	276	N.D.	<0.05	0.013	2.15	1.594
Geokinetics	EM-571-F	Raw	25.8	0.8942		218	N.D.	0.10	0.011	0.85	1.682
	EM-586-F	Filtered	26.6	0.8896	65	220	N.D.	<0.05	0.011	0.87	1.687
Union	EM-573-F	Raw	23.5[b]	0.9074	61	215	N.D.	0.10	0.028	0.85	1.634
	EM-581-F	Filtered	21.8[b]	0.9175	70	243	N.D.	<0.05	0.008	0.93	1.630

---

[a] Calculated from API gravity
[b] Result seems questionable
[c] Water-oil emulsion or sludge
[d] Small emulsion present
N.D. non-detected

9076

PHILLIPS CHEMICAL COMPANY
A SUBSIDIARY OF PHILLIPS PETROLEUM COMPANY
PETROCHEMICALS

BARTLESVILLE, OKLAHOMA 74004
PHONE: 918 661-6600 TWX 910 841-2560 TLX 49-2455

TABLE 15. PROPERTIES OF DF-2 (EM-528-F) USED FOR BASELINE TESTING

D-2 Diesel Control Fuel

Phillips Lot C-747
(SwRI EM-528-F)

	Results	EPA Specification*	Test Method
Cetane Number	47.5	42-50	D 613
Distillation Range			
IBP, °F	386	340-400	D 86
10% Point, °F	430	400-460	
50% Point, °F	506	470-540	
90% Point, °F	576	550-610	
End Point, °F	610	580-660	
Gravity, °API	35.8	33-37	D 287
Total Sulfur, wt. %	0.22	0.2-0.5	D 3120
Aromatics (FIA) vol. %	29.1	27 min.	D 1319
Kinetic Viscosity (cs) @ 40°C	2.5	2.0-3.2	D 445
Flash Point (PM), °F	157	130° min.	D 93
Particulate Matter, mg/ml	2.39	--	
Cloud Point, °F	-2	--	D 2500
Elemental Analysis, wt. %			
C	86.85		Chromatography
H	13.00		Chromatography
N	0.01		Chemiluminescence
O	0.574		Neutron Activation
C/H	6.68		Calculated

10.0 ptb (pounds/1000 barrels) of Du Pont FOA 011 antioxidant enhances the stability of this fuel.

*Diesel fuel as described in Chapter One - Environmental Protection Agency, Subsection 86.113-78, of the Code of Federal Regulations.

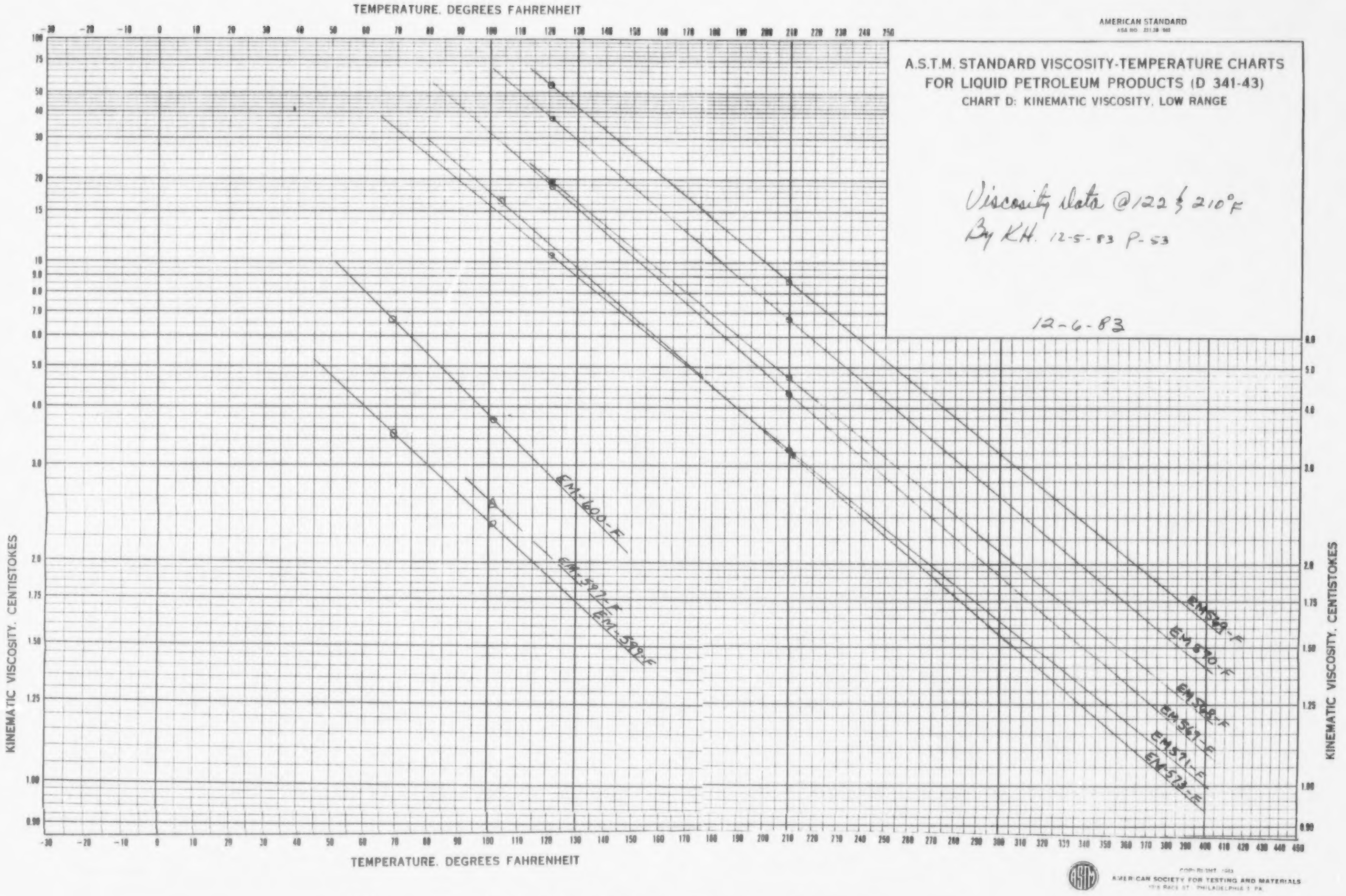


Figure 18. Viscosities of shale oil crudes before filtration

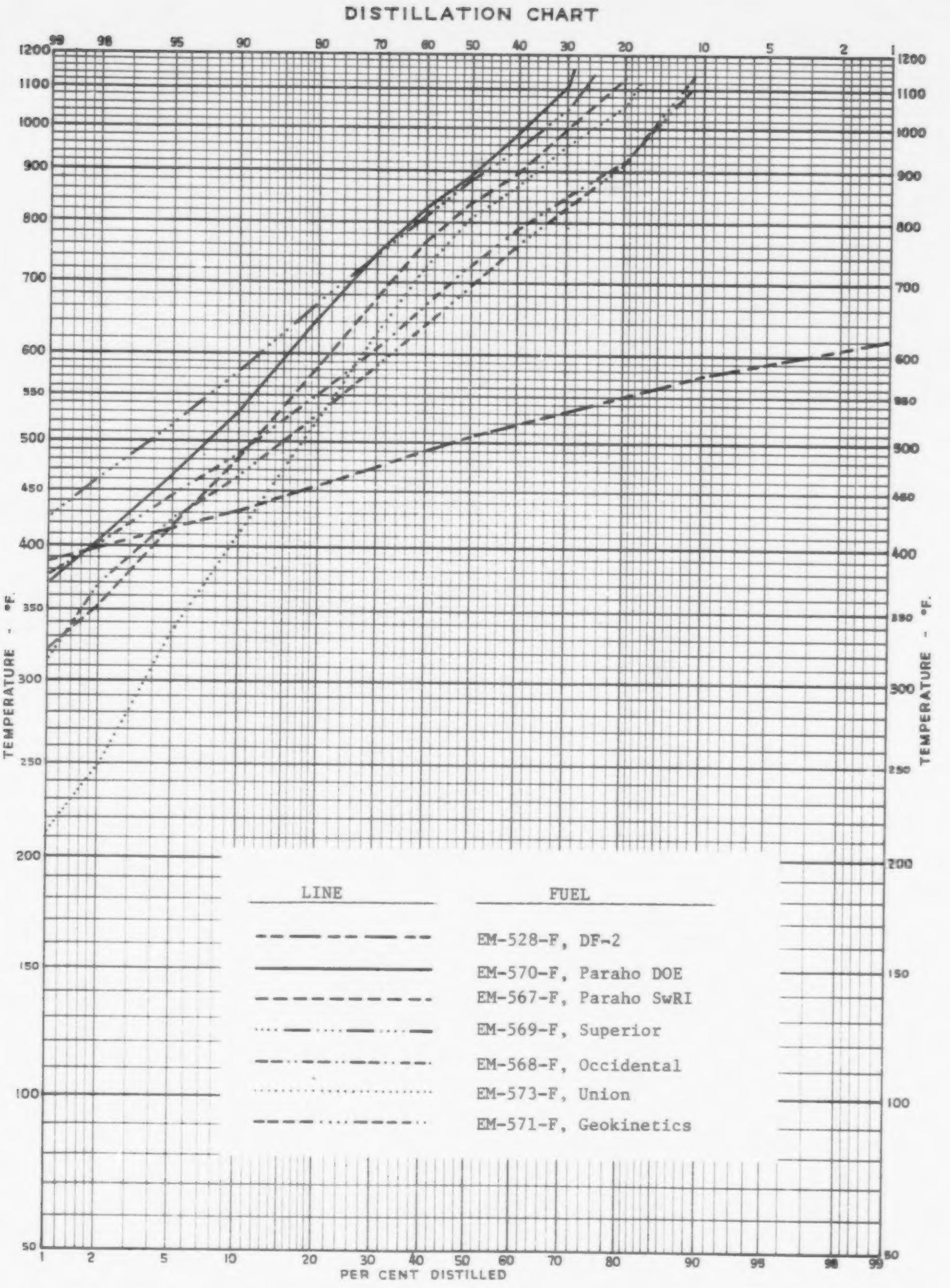


Figure 19. Boiling point distribution of shale oil crudes

D2877 procedure gives lower temperatures from the IBP to about the 20 percent point than does the D86 procedure. Similarly, the D2877 procedure gives higher temperatures for the material found beyond about 90 percent point and up to EP. Both procedures yield about the same boiling point distribution in the range of 20 to 90 percent distilled.

In addition, area distributions of the boiling point data obtained on the various shale oils are given in Figures 20, 21, and 22. The horizontal positions of the peaks in these figures indicate the presence of various HC species, determined by their occurrence at retention times coincident with peaks noted with standard petroleum crude oil (Altamont Crude). The vertical amplitudes of the peaks are only of use when compared to the amount of internal standard used during the individual analysis, and are therefore of little comparative value. Hence, the vertical scale labels "slice unit" and "mV" are only for data storage and manipulative purposes. Retention times for various molecules contained in Altamont crude standard are given in Table 16.

These figures represent groupings of similar boiling point distribution data. That is, based on similarity of the chromatographic information obtained during the boiling point distribution procedure, the six shale oils were placed into three groups. Group I contained EM-568-F and EM-571-F. Group II contained EM-567-F, EM-570-F and EM-569-F. Group III contained only EM-573-F.

There were only minor differences in the boiling point distributions between "raw" and "filtered" shale oils. Essentially, it appears that filtration reduced the amount of residue (product which would not boil off below approximately 600°C), Otherwise, all peaks present for the "raw" shale oil also appeared for the "filtered" shale oil.

Results from elemental analysis of the various shale oil materials are given in Table 17. Percentages of carbon and hydrogen were determined according to ASTM procedure D1378. Nitrogen content was determined by pyrochemiluminescence, and oxygen content of selected samples was determined by neutron activation analysis. Sulfur and other elements listed in Table 17 were determined using x-ray fluorescence by EPA-RTP as part of the in-house measurements program.

Based on the properties presented in Table 14, the shale oils were ranked in the order of "least" to "most" favorable for introduction to the engine. Of the many properties listed, viscosity was of prime concern due to the potential to seize the rotary distributor head of the engine's fuel injection pump. From reference 19, work with direct utilization of crude petroleum oils in a diesel engine using a rotary distributor fuel injection pump of the Roosa-Master type had indicated that control of viscosity was critical and that momentarily exceeding 40 cS caused seizure of the rotary distributor head. Even though filtration reduced the levels of contaminants, concentrations of water and sediment (in the form of fines) were also of concern. The percent of ash and carbon residue were of concern from the standpoint of combustion chamber deposit and cylinder liner wear.

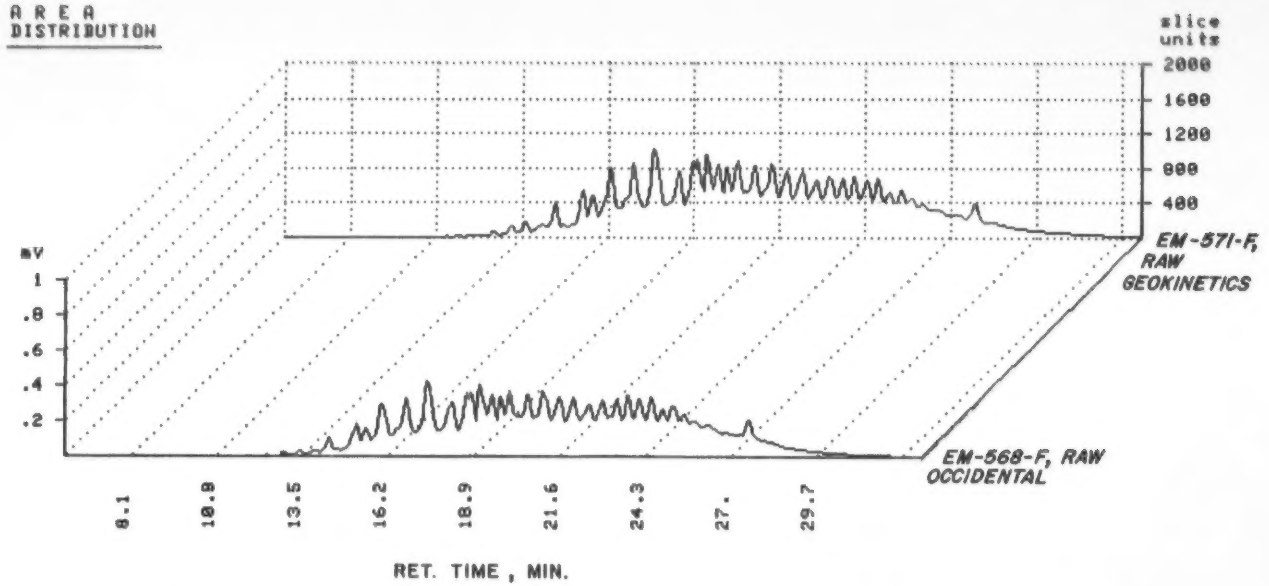


Figure 20. Area distribution of boiling point data obtained on crude shale oils from Group I

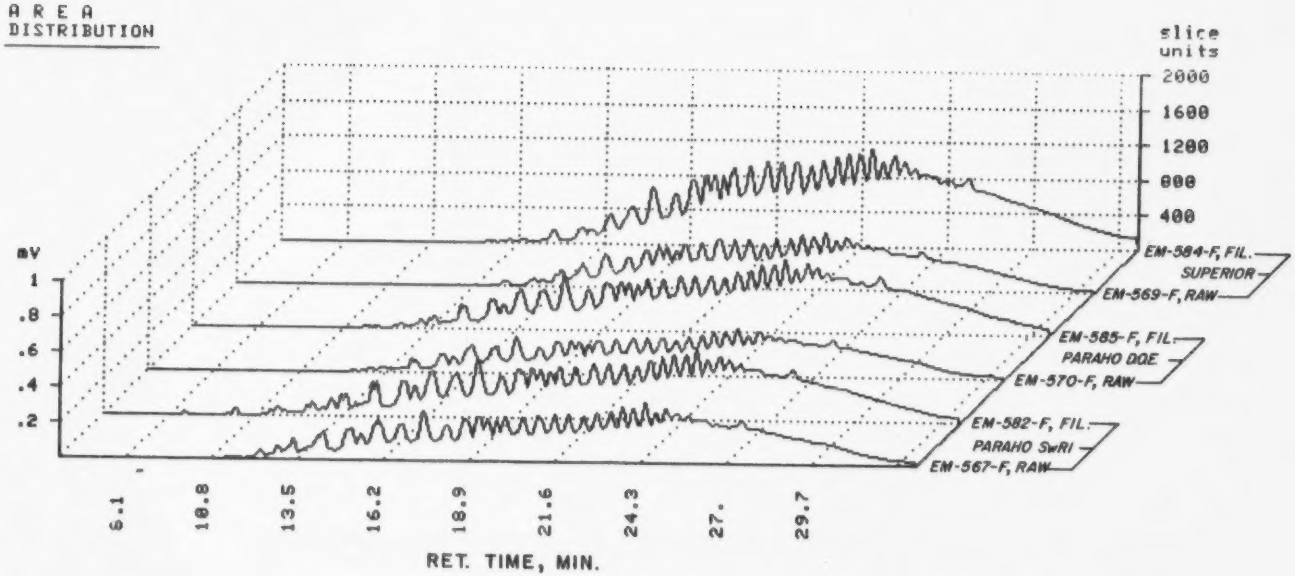


Figure 21. Area distribution of boiling point data obtained on crude shale oils from Group II

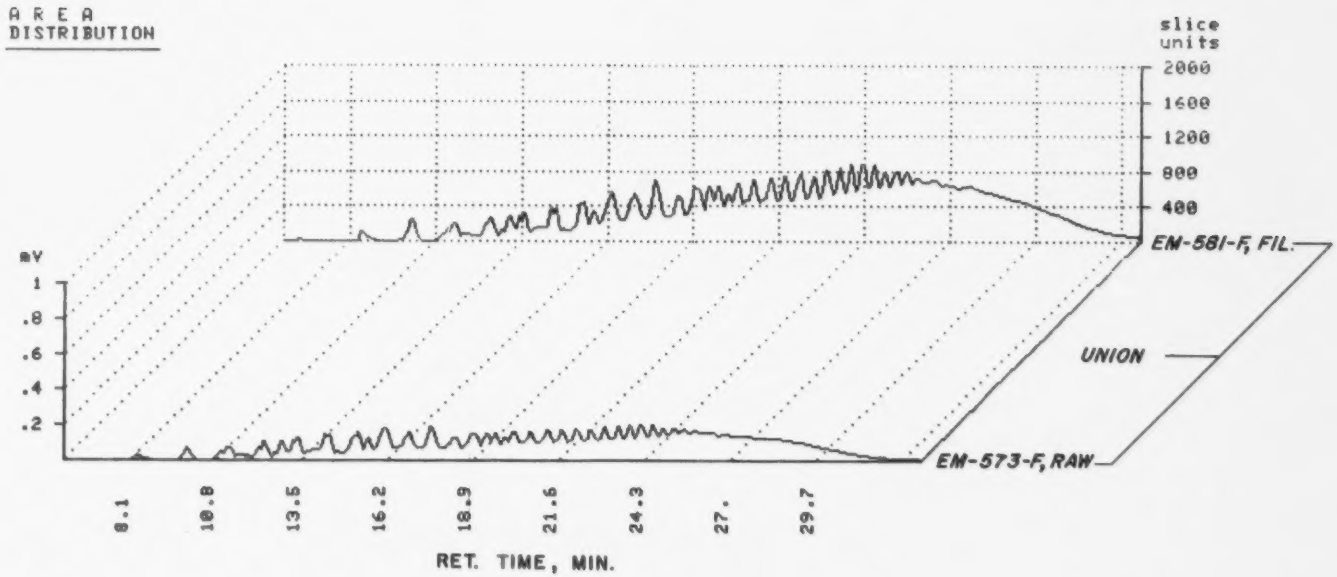


Figure 22. Area distribution of boiling point data obtained on crude shale oils from Group III

TABLE 16. BOILING POINT RETENTION TIME AND TEMPERATURES OF STANDARD CRUDE OIL (ALTAMONT CRUDE)

Retention Times Associated with Standard Crude Oil		
Retention Time, min	Carbon Number	Boiling Pt. Temp, °F
7.7	6	156
7.9	Benzene	176
9.5	7	208
10.8	8	256
11.9	9	304
13.0	10	345
14.0	11	385
14.8	12	421
15.7	13	455
16.5	14	489
17.2	15	519
18.0	16	549
18.6	17	576
19.2	18	601
19.8	19	626
20.4	20	651
22.4	24	736
24.0	28	808
25.5	32	871
26.8	36	925
28.0	40	972
29.1	44	1013
30.0	48	1050

TABLE 17. SUMMARY OF ELEMENTAL ANALYSIS OF CRUDE SHALE OILS "RAW" AND "FILTERED"

Individual Element	Paraho SwRI		Occidental		Union		Detection Tolerance	Detection Limit
	Raw EM-567-F	Filtered EM-582-F	Raw EM-568-F	Filtered EM-583-F	Raw EM-573-F	Filtered EM-581-F		
C, %	84.50	84.36	84.37	84.39	84.61	84.70	0.10%	a
H, %	11.48	11.47	11.92	11.91	11.60	11.59	0.03%	a
N, %	a	1.38	a	1.13	a	1.20	a	a
O, %	a	a	a	a	a	a	a	0.0004%
S, %	0.79	0.75	0.83	0.79	0.95	0.98	0.04%	0.0003%
Al, ppm	17[c]	b	b	b	b	b	6 ppm	16 ppm
As, ppm	36	25	14[c]	11[c]	56	54	6 ppm	6 ppm
Ba, ppm	2.8[c]	1.8[c]	b	b	b	b	2 ppm	2 ppm
Ca, ppm	92	10.5	12	11	42	8.3	2 ppm	1 ppm
Co, ppm	b	b	b	4.0[c]	b	b	3 ppm	3 ppm
Cu, ppm	7.7[c]	8.7[c]	9.2[c]	12	8.1[c]	6.2[c]	4 ppm	4 ppm
Cr, ppm	11[c]	11[c]	18	10[c]	11[c]	9.3[c]	5 ppm	5 ppm
Fe, ppm	140	100	210	120	63	50[c]	8 ppm	4 ppm
K, ppm	14	b	b	b	4.3[c]	b	0.5 ppm	2 ppm
Mg, ppm	83	b	b	b	31[c]	b	30 ppm	25 ppm
Mn, ppm	7.1[c]	3.7[c]	6.2[c]	8.0[c]	6.4[c]	4.9[c]	4 ppm	3 ppm
Ni, ppm	22	19	33	23	19	22	4 ppm	3 ppm
P, ppm	3.9[c]	b	2.7[c]	1.5	4.7[c]	2.3[c]	2 ppm	2 ppm
Sb, ppm	b	2.6[c]	b	1.9[c]	b	b	2 ppm	2 ppm
Si, ppm	1100	b	b	b	b	b	12 ppm	40 ppm
Sn, ppm	6.7[c]	7.6[c]	b	b	b	4.1[c]	4 ppm	4 ppm
Ti, ppm	3.6	0.7[c]	0.8[c]	0.9[c]	1.5[c]	b	0.6 ppm	0.6 ppm
Zn, ppm	4.1[c]	5.9[c]	6.0[c]	7.5[c]	7.9[c]	b	4 ppm	4 ppm

NOTE: The following were below the detection limit given for each Br 22 ppm, Cd 2 ppm. Cl 13 ppm, Na 1700 ppm, Pb 95 ppm, Se 7 ppm, Sr 60 ppm, V 3 ppm

[a] No data
[b] Element below the detection limit
[c] Element detected, but was below the level of quantitation (3 x detection limit)

TABLE 17 (Cont'd). SUMMARY OF ELEMENTAL ANALYSIS OF CRUDE SHALE OILS "RAW" AND "FILTERED"

Individual Element	Superior		Geokinetics		Paraho DOE		Detection Tolerance	Detection Limit
	Raw EM-569-F	Filtered EM-584-F	Raw EM-571-F	Filtered EM-586-F	Raw EM-570-F	Filtered EM-585-F		
C, %	84.11	84.14	85.14	85.05	82.41	84.87	0.10%	a
H, %	11.09	11.16	12.02	12.04	11.28	11.35	0.03%	a
N, %	a	1.59	a	1.12	a	1.82	a	a
O, %	a	1.85	a	0.797	a	0.951	a	0.0004%
S, %	0.84	0.84	0.66	0.67	d	0.71	0.04%	0.0003%
Al, ppm	b	b	b	b	d	b	6 ppm	16 ppm
As, ppm	24	20	16[c]	18[c]	d	21	6 ppm	6 ppm
Ba, ppm	2.5[c]	b	b	b	d	b	2 ppm	2 ppm
Ca, ppm	24	14	8.3	12	d	7.9	2 ppm	1 ppm
Co, ppm	b	b	b	3.6[c]	d	b	3 ppm	3 ppm
Cu, ppm	6.8[c]	13	11[c]	6.1[c]	d	9.0[c]	4 ppm	4 ppm
Cr, ppm	12[c]	18	10[c]	11[c]	d	13	5 ppm	5 ppm
Fe, ppm	220	190	95	93	d	110	8 ppm	4 ppm
K, ppm	2.3[c]	b	b	b	d	b	0.5 ppm	2 ppm
Mg, ppm	b	b	b	b	d	b	30 ppm	25 ppm
Mn, ppm	5.9[c]	3.3[c]	5.4[c]	b	d	b	4 ppm	3 ppm
Ni, ppm	22	24	23	25	d	22	4 ppm	3 ppm
P, ppm	2.3[c]	b	b	b	d	2.3[c]	2 ppm	2 ppm
Sb, ppm	b	b	b	b	d	b	2 ppm	2 ppm
Si, ppm	b	b	b	b	d	b	12 ppm	40 ppm
Sn, ppm	b	b	b	4.9[c]	d	b	4 ppm	4 ppm
Ti, ppm	1.3[c]	b	b	b	d	b	0.6 ppm	0.6 ppm
Zn, ppm	b	5.6[c]	b	5.9[c]	d	12	4 ppm	4 ppm

NOTE: The following were below the detection limit given for each Br 22 ppm, Cd 2 ppm, Cl 13 ppm, Na 1700 ppm, Pb 95 ppm, Se 7 ppm, Sr 60 ppm, V 3 ppm

[a] No data

[b] Element below the detection limit

[c] Element detected, but was below the level of quantitation (3xdetection limit)

[d] Sample not processed due to inability of sample to form a grease when mixed with lithium stearate

On the basis of the characteristics given in Table 14, scoring the crude filtered shale oils yielded the "best" candidate as EM-571-F (Geokinetics), then EM-573-F (Union), EM-583-F (Occidental), EM-585-F (Paraho DOE), EM-582-F (Paraho SwRI), and finally EM-584-F (Superior). Depending on the outcome of engine operation on this "best" material, the "worst" candidate was selected for subsequent engine operation, thereby covering the range of properties available over the six crude shale oils on hand. The "best" candidate, "filtered" Geokinetics, (EM-586-F) was obtained from an in situ retort and had an API gravity of 26.6°, a pour point of 65°F, no water, less than 0.05 percent sediment, 0.011 percent ash, 0.87 percent carbon residue, and a H/C ratio of 1.68. In contrast, the "worst" candidate, "filtered" Superior (EM-584-F), was obtained from a rotating grate surface retort and had an API gravity of 18.5°, a pour point of 90°F, 0.5 percent water, less than 0.05 percent sediment, 0.026 percent ash, 3.12 percent carbon residue, and a H/C ratio of 1.58. To obtain a kinematic viscosity approximately equivalent to that of No. 2 diesel fuel (around 3 centistrokes), the Geokinetics and Superior shale oils had to be heated to 220 and 320°F, respectively. The remaining crude shale oils had properties between these extremes.

Pour points of crude shale oils in general vary with the methods of operation of the retort as well as with origin of the raw shale. Typically , high pour points are due to the presence of normal paraffins. In situ-retorted shale oils tend to have lower pour points than do surface-retorted oils.(19), which is in agreement with the pour points established for the six crude shale oils used in this program. Similarly, the two in situ retorted oils (Geokinetics and Occidental) had relatively low carbon residue. In situ-derived shale oils generally contain less 1000°F + residuum than do shale oils produced in above ground retorts(19). It is interesting to note that the properties of the Union (EM-581-F) shale oil, which was obtained from the Unishale B process, approach those associated with in situ processes.

Shale oils contain many olefins (as obtained from cracking petroleum) as well as nitrogen compounds, and tend to be unstable. This composition compares to petroleum crude, which has very few olefins until it undergoes cracking in a refinery. Slow retorting of large size shale (in an in situ retort) results in considerably less residuum, and some coking also occurs. This coking reduces the heteroatom impurity concentrations which affects the stability of the crude shale oils.(19) From the chromatograms (Figures 20, 21, and 22) of the six crude shale oils, the bulk of the boiling point distribution for Geokinetics and Occidental in situ-retorted materials occurs between 16 and 26 minutes retention time (coinciding with material of 14 to 26 carbon number). After the 26 minute retention time, the chromatogram tapers off. Examining Figure 19 along with retention time data given in Table 16, about 80 percent of the Geokinetics and Occidental materials boils off below 925°F, coinciding with material having a carbon number of less than 36 (which is eluted at a retention time of 26.8 minutes). About 68 percent of the Union material boiled off below 925°F (carbon number of 36). The remaining crude shale materials (Superior, Paraho SwRI and DOE) had approximately 63, 57 and 54 percent boil off at 925°F, respectively. These results indicate that the surface-retorted shale oils did have larger amounts of high boiling point materials than the in situ-retorted shale oils.

Elemental composition of the crude shale oil material is also dependent on both the origin of the shale and the retorting process. Of the six filtered crude shale oils, the in situ-retorted materials had lower nitrogen, and oxygen content. Nitrogen ranged from 1.12 percent for the Geokinetics to 1.82 percent for the Paraho DOE. Oxygen content (not all samples analyzed) ranged from 1.85 percent for the Superior to 0.80 percent for the Geokinetics. The filtered Geokinetics material had the lowest sulfur content at 0.67 percent, and the Union material had the highest at 0.98 percent.

Crude shale oil contains a great variety of metals in the form of metallic compounds. These metallic contaminants may contribute to corrosive reactions and abrasion in the engine. Many of these metals are also of concern from the standpoint of refinery catalyst contamination, but metals such as arsenic may also pose health problems when or if these crudes are burned. The concentration of arsenic in the six crude shale oils received ranges from a high of 56 ppm to a low of 11 ppm. The arsenic compounds are volatile and distributed throughout the entire boiling range of the shale oil(19) (Typical petroleum crudes and DF-2 do not contain significant quantities of arsenic). In contrast to arsenic, iron and (to some extent) nickel are found mainly in the heaviest fraction (950°F +) of the shale oil.(19) These and other metals may be present as fines, but may also be bonded in organic compounds.(19) Some reduction in the level of contaminant content was noted after filtration and it is assumed that both suspended solids (sediment) and heavy ends were trapped in the filtration system.

D. Background Information on and Properties of Two Minimally-Processed Shale Oils

Some specification fuels and gasoline have been refined from crude shale oil for evaluation as replacements for petroleum-based products. Although the feasibility of obtaining specification products from crude shale oil has been demonstrated, it has also been demonstrated that the cost of refining crude shale oil to specification quality products is comparatively high. Crude shale oil differs from petroleum crude oil in that a larger portion of the crude shale oil consists of HC molecules favorable for use as diesel fuel. In this regard, it was hoped that crude shale oil could be consumed without detrimental effects on the engine or emissions. Since problems exist with such a scenario, it was hoped that some form of minimally-processed crude shale oil (syncrude) could be used as a diesel fuel substitute. The ability to consume minimally-processed shale oils, as opposed to carrying the refinery process of the shale oil out to obtain specification quality fuels, would be expected to substantially reduce the cost of utilizing shale oil. Two minimally-processed shale oils were obtained from Geokinetics Inc. Caribou refinery through the DOE-NASA Synthetic Fuels Center for this program. Both were taken from intermediate steps in the refining of crude shale oil to specification products.

Geokinetics was contracted by the DFSC (Defense Fuels Supply Center) to refine 82,000 barrels of crude shale oil (34,000 barrels from Geokinetics and 48,000 barrels from DFSC stockpile at Anvil Points, Co.) into a slate of products meeting military specifications. The Caribou Four Corners refinery was expected to produce 43,000 barrels of JP-4, 1500 barrels of DF-2, and 3000 barrels of gasoline. This refinery was relatively small, with a processing capacity of 8000 barrels/day of normal feedstock (high quality, high gravity, low sulfur crude oil). Figure 23 illustrates the layout of the plant. The principal components of the refinery were the crude distillation unit, a hydrocracker for cracking the gas oil, and reformers for making no-lead gasoline. Hydrogen for the hydrocracker was provided by the reformers, but the refinery was modified to handle crude shale oil by the construction of reliable hydrogen plant to supply high purity hydrogen. Two hydrotreating reactors and a guard bed were added to the hydrocracker, and additional storage and blending tanks were constructed.(22)

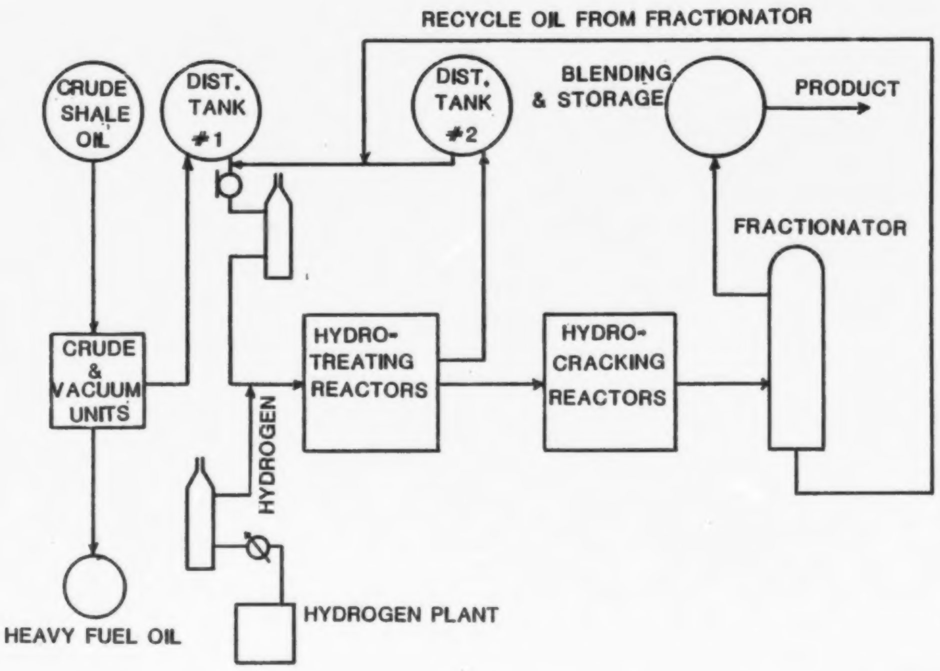

RECYCLE OIL FROM FRACTIONATOR
CRUDE SHALE OIL
DIST. TANK #1
DIST. TANK #2
BLENDING & STORAGE
PRODUCT
FRACTIONATOR
CRUDE & VACUUM UNITS
HYDRO-TREATING REACTORS
HYDRO-CRACKING REACTORS
HYDROGEN
HYDROGEN PLANT
HEAVY FUEL OIL

Figure 23. Block diagram of Geokinetics - Caribou Shale Oil Refining Process

The refining was done in two passes through the system. Crude shale oil first went through a vacuum distillation unit where 20 percent (the highest boiling fraction) was separated and collected as heavy fuel oil. The remaining 80% was stored in Distillate Tank No. 1(22). Shale oil from this tank was one of the minimally-processed fuels used in this program, and was labeled as "Distillate Shale Crude" and coded as SwRI EM-600-F. The oil in Distillate Tank No. 1 was heated, mixed with hot hydrogen, passed through a guard bed and a hydrotreated, and then accumulated in Distillate Tank No. 2. At this point, the metals had been removed, and the nitrogen content of the oil has been greatly reduced.(22) It was at this point that the other minimally-processed fuel for use in this program was drawn and labeled as "High Nitrogen Hydrocracker Feed" and coded as SwRI EM-599-F. To continue for specification products, the oil from Distillate Tank No. 2 was run through a guard bed and hydrotreated a second time. Then the oil went directly through the hydrocracker section and on to a fractionator, where the desired products are removed for storage or blending and the bottoms are recycled back through the unit.(22)

Properties of the two minimally-processed shale oils are given in Table 18. For comparison purposes, the properties of the DF-2 (EM-597-F) used in establishing the baseline performance and emissions levels from the DT-466B after rebuild for this follow-on work, are given in Table 19. Overall, both intermediate shale oil products had good cetane number, and other properties which were expected to pose few problems in the engine.

The Distillate shale crude (EM-600-F) had a reasonable API gravity compared to that of No. 2 diesel fuel specifications. Kinematic viscosity was slightly above normal for diesel fuel, but was not of the same magnitude as the relatively high values encountered with the crude shale oils. Water content was sufficiently low, and sediment and ash were well under control so no preliminary fuel filtering prior to introduction was deemed necessary. The flash point was relatively low at 66°F compared to the flash points above 125°F for most No. 2 diesel.

In addition, relative to No. 2 diesel fuel, the Distillate (EM-600-F) contained about 10 percent light ends (under 340°F) and just in excess of 30 percent heavy ends (over 660°F). This minimally-processed material had a good percentage of hydrogen and carbon with H/C mole ratio of 1.76. Nitrogen content of the Distillate was high compared to finished diesel fuel, and at 1.23 percent resembled the level noted for the Geokinetics crude shale oil. Similarly, the sulfur and oxygen levels for EM-600-F resembled the levels obtained for the Geokinetics crude shale oil. Iron content of the Distillate shale crude was only 16 ppm, substantially lower than the levels noted for most of the crude shale oils (which averaged near 100 ppm). The Distillate shale oil was black and opaque, so FIA analysis was impossible. It had a strong odor, characteristic of most of the crude shale oils.

The High Nitrogen Hydrocracker Feed (HNHF) (EM-599-F) was clear in color and did not have much odor (as associated with crude shale oil). The nitrogen content of EM-599-F was only 0.05 percent. (The DF-2 (EM-597-F) had a nitrogen content of 0.08 percent). The labeled identification of EM-599-F, High Nitrogen Hydrocracker Feed designates high nitrogen content of the material with respect to catalytically hydrocracking this material at the refinery. The API gravity was high at 44.9, compared to EPA specification for No. 2 diesel fuel, so the specific gravity of this material was considered low. The kinematic viscosity of the HNHF was in the range of EPA-specified No. 2 diesel fuel. Contaminants of water, sediment, and ash were all very low or non-existent, and no additional filtering was deemed necessary for this hydrotreated distillate shale material prior to use in the engine. The flash point for the HNHF (EM-599-F) was even lower than for the Distillate crude shale oil (EM-600-F).

TABLE 18. ANALYSIS OF DISTILLATE SHALE CRUDE AND HIGH NITROGEN HYDROCRACKER FEED FROM CARIBOU REFINERY

PROPERTIES	EM-600-F DISTILLATE SHALE CRUDE	EM-599-F HIGH NITROGEN HYDROCRACKER FEED
Gravity, deg API	32.1	44.9
Specific gravity at 15.6 deg C	0.8649	0.8022
Distillation, deg C, D 86 (D 2887 values in parentheses)		
Initial boiling point	83 (69)	73 (28)
10 % recovered	205 (201)	154 (150)
20 % recovered	231 (235)	216 (215)
50 % recovered	278 (295)	266 (277)
90 % recovered	361 (390)	329 (361)
End point	392 (474)	378 (461)
% residue from D 86,	2	2
Kinematic viscosity at 20 deg C, cSt	6.51	3.46
Kinematic viscosity at 40 deg C, cSt	3.74	2.32
Water content, vol %	0.08	0.04
Sediment, vol%	0	0
Ash, wt %	0.001	>0.001
Total acid number, mg KOH/g	0.55	0
Cetane number	41	58
Pour point, deg C	-1	0
Cloud point, deg C	too dark	10
Flash point, deg C	19	<0
Carbon residue, wt % (whole sample)	0.12	0.03
Bromine number	19.18	0.18
Pentane insolubles, wt %	0.10	0.01
Toluene insolubles, wt %	0.01	0.01
Carbon, wt%	85.22	85.52
Hydrogen, wt %	12.56	14.25
Sulfur, wt %	0.52	<0.01
Nitrogen, wt %	1.23	0.05
Oxygen, wt %	0.71	0.02
Iron, ppm	16	ND*
FIA		
Olefins, %	--	1.0
Saturates, %	--	88.4
Aromatics, %	--	10.6

ND, not detected

TABLE 19. PROPERTIES OF DF-2 (EM-597-F) USED FOR BASELINE TESTING

Laboratory Test Report

PHILLIPS CHEMICAL COMPANY
A SUBSIDIARY OF PHILLIPS PETROLEUM COMPANY

BARTLESVILLE, OKLAHOMA 74004

DATE OF SHIPMENT 4-12-84
CUSTOMER ORDER NO. 33044
INV. OR REQN. NO. 00996S

EM-597-F
Diesel D-2 DCF
Lot No. G-075

Test	Results	EPA Specifications
Density, g/ml	0,8488	
API Gravity, 60 F	35.2	33 - 37
Sulfur, Wt%	0.35	0.2 - 0.5
Particulate Matter, mg/liter	2.07	
Pour Point, F	0	
Kinematic Viscosity, 40° C, CS	2.52	2.0 - 3.2
Flash Point, PM, F	162	130 Min.
Cloud Point, F	+12	
Distillation, D-86, °F		
IBP	375	340 - 400
5%	415	
10	431	400 - 460
20	451	
30	469	
40	487	
50	505	470 - 540
60	523	
70	543	
80	567	
90	598	550 - 610
95	628	
DP	648	
EP	653	580 - 660
Composition, Vol% by FIA		
Aromatics	32.10	27 Min.
Olefins	1.33	
Paraffins & Naphthenes	66.57	
Cetane Number	46.2	42 - 50
Elemental Analysis, wt, %		
Carbon	86.12	
Hydrogen	12.92	
Nitrogen	0.08	
Oxygen	0.06	
C/H	6.66	

FORM 8826-N 1-81

Relative to No. 2 diesel fuel, about 15 percent of the high nitrogen hydrocracker feed had a boiling range below the IBP (340-400°F) typical of most No. 2 diesel fuels. In addition, another 15 percent of this material had a boiling range above the EP (580-660°F) associated with No. 2 diesel fuel. Being hydrotreated, this material (EM-599-F) had about the same percentage of carbon but a substantial increase in hydrogen content compared to the distillate crude shale oil. The HNHF, EM-599-F, had a H/C mole ratio of 1.99. Based on FIA analysis of EM-599-F, saturates accounted for 88.4 percent, along with 10.6 percent aromatics, and 1 percent olefins. At this point in the refining process, sulfur content of HNHF was essentially nil, and was recorded as less than 100 ppm.

In addition to the data given in Tables 18 and 19 for the two minimally-processed fuels (EM-599-F and EM-600-F) and for the DF-2 (EM-597-F), samples of these fuels were analyzed for boiling point distribution using both ASTM D2887 and D86 procedures. Figure 24 shows the boiling point distribution of all three fuels based on the ASTM D86 procedure. Figure 25 shows the boiling point distribution of the two minimally-processed shale oils based on the ASTM D2887 procedure. (DF-2 was not submitted for analysis by ASTM D2887). The boiling points of various HC species are also indicated in Figure 25. Generally, the ASTM D2887 procedure gives lower temperatures for the IBP to about the 20 percent point than does the ASTM D86 procedure. In addition, the ASTM D2887 procedure gives higher temperatures for the material found beyond about the 90 percent point to the EP. Both procedures yield about the same boiling point distribution in the range from 20 to 90 percent boiling point.

Boiling point distribution by both procedures indicated the presence of some low boiling range components (below 350°F, which coincides with the approximate IBP of DF-2 by D86) in both the Distillate crude shale oil (EM-600-F) and High Nitrogen Hydrocracker Feed (EM-599-F). For EM-600-F, these low boiling range components make up about 2-6 percent of the total, and for EM-599-F they account for about 12-13 percent. The end point for DF-2 (EM-597-F) by D86 was approximately 650°F. For EM-600-F about 7 percent (by D86) and 13 percent (by D2887) had a boiling point temperature above 650°F. For EM-599-F, however, about 15 percent (by D86) and 24 percent (by D2887) had a boiling point temperature above 650°F. By D86, the end point for EM-600-F was about 810°F with about 4 percent residue; and the end point of EM-599-was about 705°F with about 2 percent residue. By D2887, end points (99 percent boiling point) were about 840°F for EM-600-F and 810°F for EM-599-F.

In addition, area distributions of boiling point data obtained on the two minimally-processed shale oils by ASTM D2887 are given in Figure 26 . The horizontal positions of the peaks in this figure indicate the presence of various HC species, determined by their occurrence at retention times coincident with peaks noted for a standard containing HC species from C3 to C40, including benzene. The vertical amplitudes of the peaks indicate the relative amounts of material corresponding to the various retention times for that material. Vertical scale labels "slice units" and "mV" are only for data storage and manipulative purposes. Retention times for various molecules contained in the standard are given in Table 20 along with their boiling point temperatures.

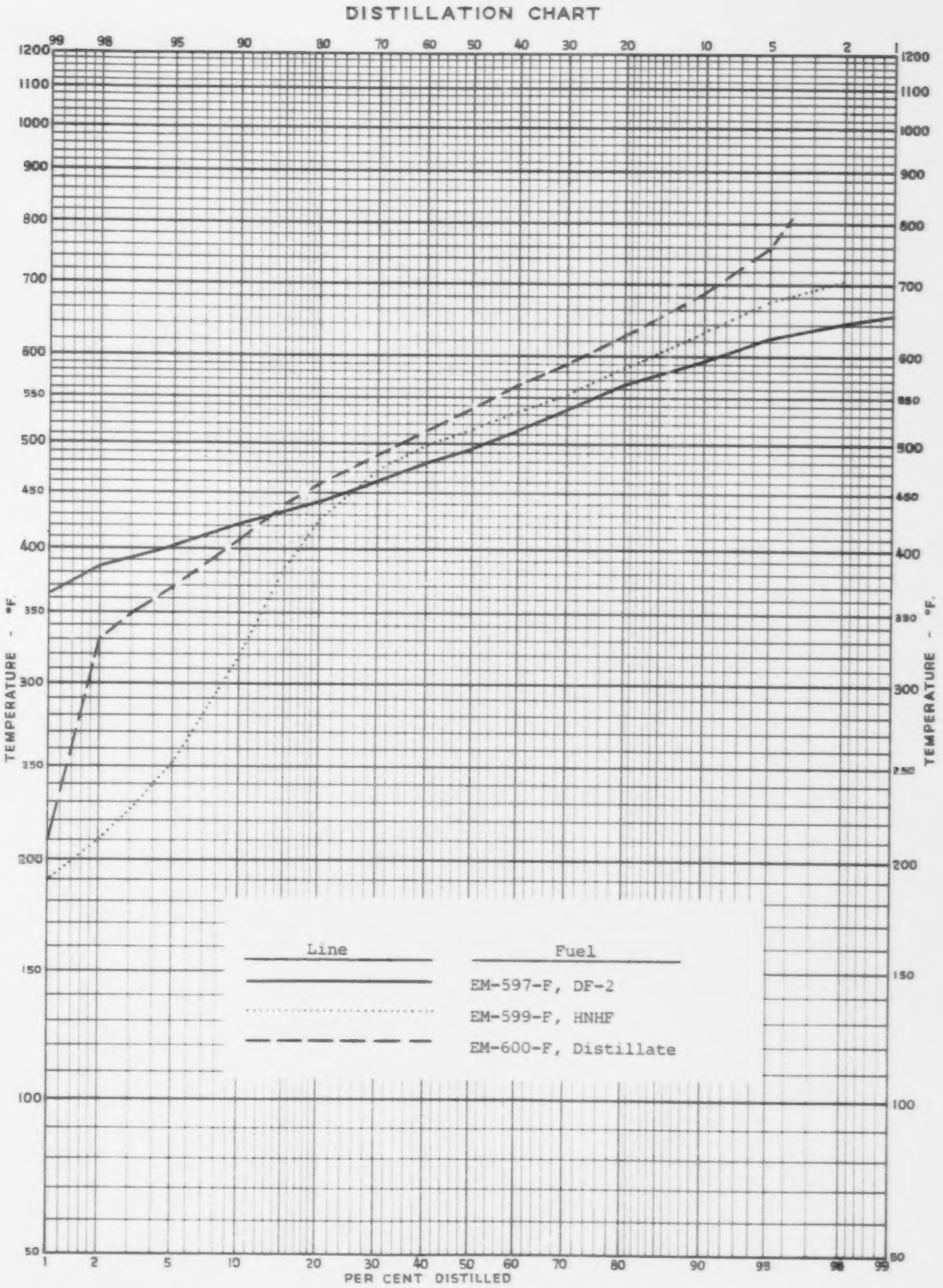


Figure 24. Boiling point distribution of minimally-processed shale oils based on ASTM D86

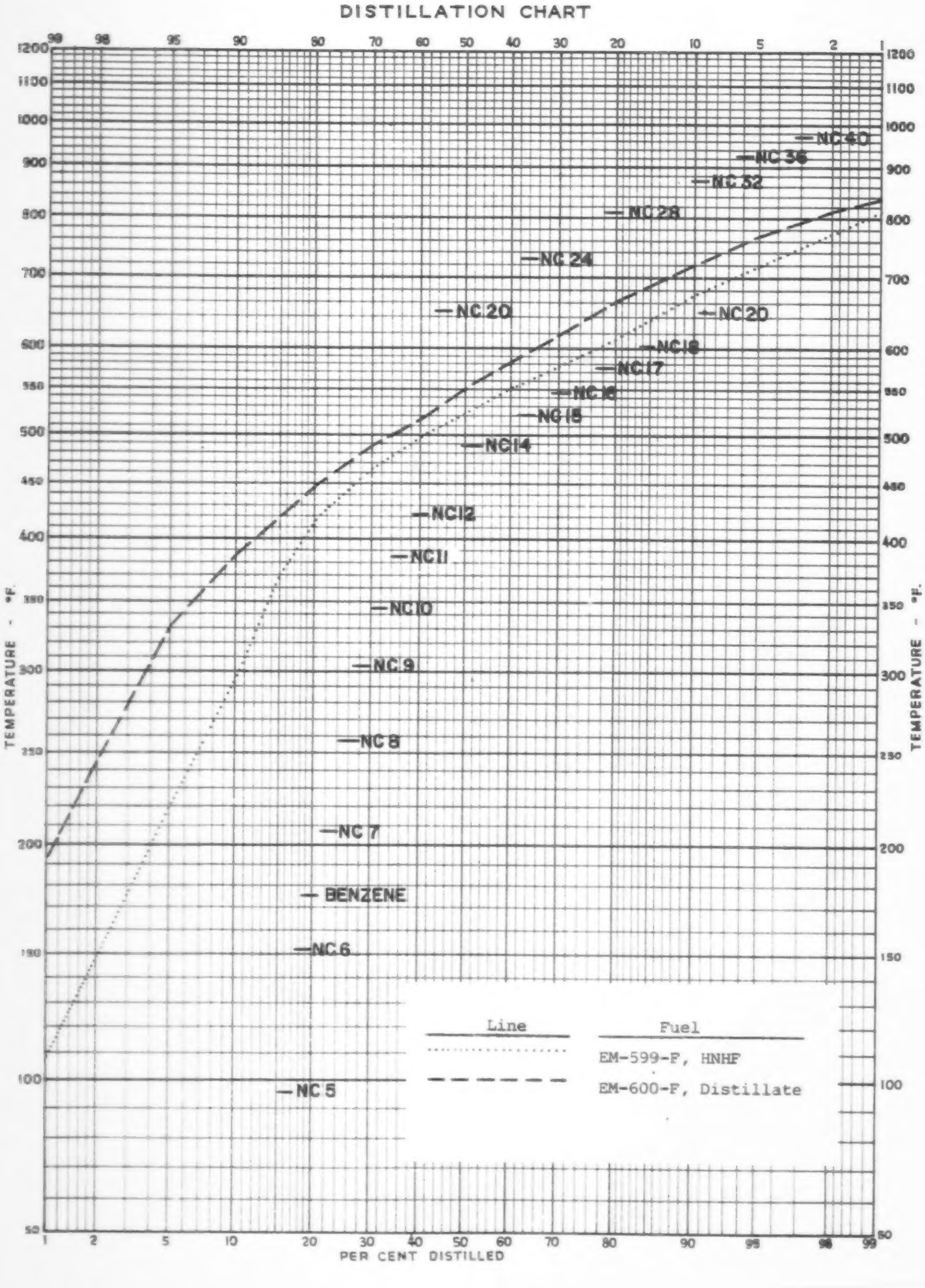


Figure 25. Boiling point distribution of minimally-processed shale oils based on ASTM D2887

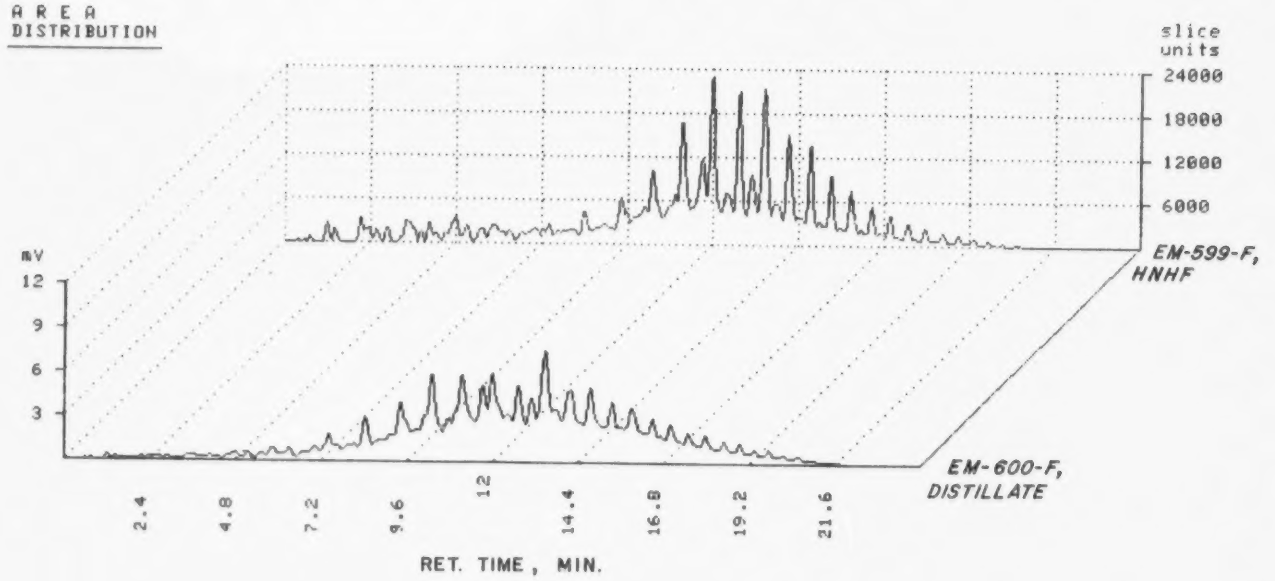


Figure 26. Area distribution of boiling point data (D2887) obtained on two minimally-processed shale oils

From the distillation chart (Figure 25) and the area distributions of boiling point data (Figure 26), most of the two minimally-processed shale oils are made up of molecules which have boiling points similar to that of straight chain paraffins with carbon numbers ranging from 12 to 20. This coincides with 20 to 80 percent distilled. It would appear that the effect of hydrotreating the Distillate crude shale oil (EM-600-F) was to shift it to lighter ends. From the area distribution plots, EM-599-F (hydrotreated EM-600-F), an increase in peak definition may be noted during the early retention times which coincides with light ends. Also, peaks representing molecules with 12 to 20 carbon atoms appear to be more defined. That is, HNHF (EM-599-F) appears to contain more organized paraffinic type molecules than Distillate (EM-600-F), with generally a slight shift to lighter boiling range material than noted for EM-600-F.

Samples of both EM-600-F and EM-599-F were submitted for determination of sulfur and other elements (x-ray fluorescence) by EPA-RTP as part of the in-house measurements program. Results from these analyses, along with results for carbon, hydrogen, nitrogen, oxygen and sulfur (given earlier in Table 18) are given in Table 21. Considering the metals, traces of aluminum and arsenic were reduced. Some reduction of silicon also occurred with the hydrotreating process.

TABLE 20. BOILING POINT RETENTION TIME AND TEMPERATURES OF (C3-C40 + BENZENE) STANDARD

Retention Time Associated with C3-C40 + Benzene Standard for D2887		
Retention Time, min	Carbon Number	Boiling Pt. Temp., °F
0.4	3	-41
0.8	4	32
1.5	5	96
2.6	6	156
3.2	Benzene	176
3.9	7	208
5.2	8	259
6.4	9	303
7.5	10	345
8.5	11	385
9.5	12	421
11.2	14	489
12.0	15	520
12.8	16	548
13.4	17	576
14.1	18	601
15.3	20	651
17.5	24	736
19.4	28	808
21.0	32	871
22.4	36	925
23.7	40	972

TABLE 21. SUMMARY OF ELEMENTAL ANALYSIS OF MINIMALLY-PROCESSED SHALE OILS

Individual Element	HNHF EM-599-F	Distillate EM-600-F	Detection Tolerance	Detection Limit
C, %	85.52	85.22	0.10%	a
H, %	14.25	12.56	0.03%	a
N, %	0.05	1.23	a	a
O, %	0.02	0.71	a	0.0004%
S, %	<0.01[d]	0.52[e]	0.04%	0.0003%
Al, ppm	b	8.4[c]	6 ppm	3 ppm
As, ppm	b	8.0[c]	6 ppm	6 ppm
Ba, ppm	b	b	2 ppm	2 ppm
Ca, ppm	9.2	9.9	1 ppm	0.5 ppm
Cl, ppm	b	6.7[c]	2 ppm	2 ppm
Co, ppm	b	b	3 ppm	4 ppm
Cu, ppm	5.2[c]	4.0[c]	4 ppm	4 ppm
Cr, ppm	13[c]	11[c]	5 ppm	4 ppm
Fe, ppm	78	78	6 ppm	4 ppm
K, ppm	1.5[c]	2.0	0.3 ppm	0.8 ppm
mg, ppm	b	b	30 ppm	20 ppm
Mn, ppm	6.4[c]	4.8[c]	4 ppm	3 ppm
Ni, ppm	5.1[c]	7.5[c]	3 ppm	3 ppm
P, ppm	b	b	2 ppm	5 ppm
Sb, ppm	b	b	2 ppm	2 ppm
Si, ppm	20[c]	57	10 ppm	12 ppm
Sm, ppm	b	b	3 ppm	3 ppm
Ti, ppm	b	1.2[c]	0.6 ppm	0.6 ppm
Zn, ppm	b	b	4 ppm	4 ppm

Note: The following were below the detection limit given for each
Br 12 ppm, Cd 0.5 ppm, Hg 20 ppm, Na 800 ppm, Pb 23 ppm,
Se 7 ppm, Sr 16 ppm, V 3 ppm

[a] No data

[b] Element below the detection limit

[c] Element detected, but was below the level of quantitation (3 x detection limit)

[d] Sulfur was 48 ppm by x-ray analysis

[e] Sulfur was 5300 ppm by x-ray analysis

76
blank

V. EMISSIONS RESULTS FROM OPERATION ON SELECTED CRUDE SHALE OILS

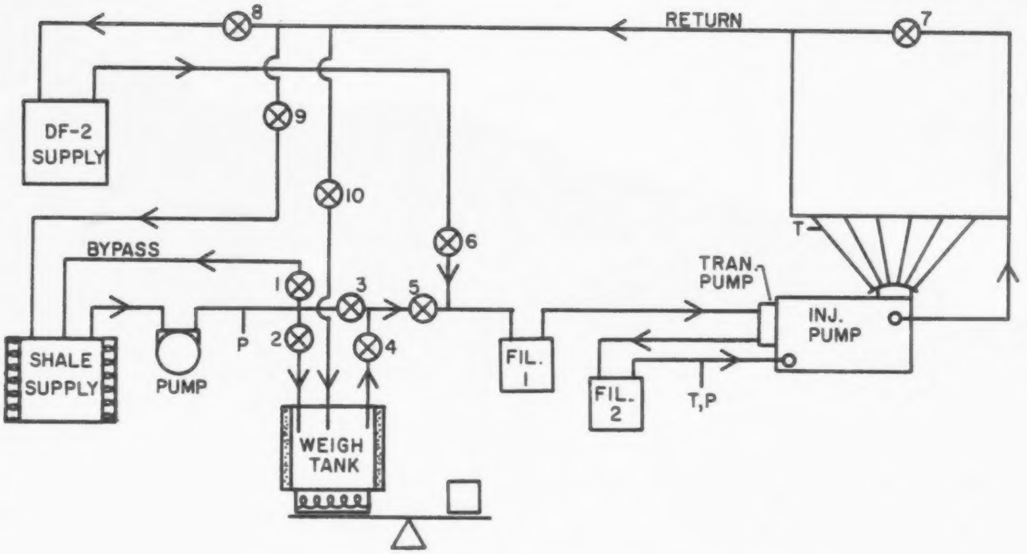
This section gives emissions results obtained during the fuel screening and testing portions of the program, along with test notes which describe fuel temperature ranges used and steps taken to maintain suitable engine operation during testing. Detailed analyses of exhaust emissions obtained over hot-start transient testing on the baseline and shale oils are given, first for gaseous emissions and then for particulate-related emissions.

A. General Test Notes

The diesel engine has been shown to be an exceptionally "fuel tolerant" engine with respect to generating mechanical work (excluding durability). The military has sponsored experiments in which crude petroleum oil was introduced into diesel engines, to study the effects on engine performance and wear in the event that crudes were used in an emergency situation.(18,20,21) In addition, the Department of Energy has sponsored work on the use of off-specification fuels in emergency situations.(21) Converting crude shale oil to specification grade finished products involves much additional cost over obtaining these finished products from petroleum crude oils. Most published work with shale oils has been concerned with introducing shale oil-derived finished diesel fuel, jet fuel, or gasoline to essentially unmodified engines. Interest had also been expressed, however, in the possibility of running a heavy-duty diesel engine on crude shale oil or minimally-processed shale oil to investigate engine operation and emissions. Approximately 110 gallons of each of six different crude shale oils were received for use in this program. It was intended that at least three of these "fuels," along with diesel fuel, would be used in the International Harvester DT-466B heavy-duty diesel engine for the purpose of characterizing the resulting exhaust emissions.

Based on reported diesel engine operation on crude petroleum oil, it was uncertain whether or not the DT-466B would operate for more than a few minutes on crude shale oil. If the "fuel" made it through the injection pump and injectors, it was thought that the engine might seize due to the formation of tar-like deposits in the combustion chamber and ring lands, breaking down the lubrication between the rings and cylinder liners. Based on these potential problems, a simple "fuel screening" was run on the engine to see if engine operation was even possible on crude shale oil.

After establishing that the engine operated properly on DF-2 (EM-528-F) using the normal fuel circuit described in Figure 4, preparations were made for preliminary screening of crude shale oils. A fuel switching system was incorporated to allow for engine start-up and shut-down on DF-2. Provisions were made to measure the crude shale oil fuel flow. The engine fuel filters, injection pump, and individual injector lines were wrapped with heater tapes (364 watts each) for temperature control of the shale oil to the injectors (210-320°F). A provision to purge shale oil from the injector spillage circuit was also incorporated. Figure 27 shows the modified fuel circuit and Figure 28 shows the engine as configured for initial crude shale oil screening.


RETURN
8
7
DF-2 SUPPLY
9
10
6
BYPASS
1
3
5
2
4
P
SHALE SUPPLY
PUMP
WEIGH TANK
FIL. 1
FIL. 2
T,P
TRAN. PUMP
T
INJ. PUMP

Valve Identification

1	Bypass Adjust
2	Weigh Tank Fill
3	Select Weigh Tank or Bulk Supply
4	Weigh Tank Out
5	Shale Oil
6	DF-2
7	Injector Spillage Purge
8	Spillage Return, DF-2
9	Spillage Return, Shale Oil
10	Spillage Return to Weigh Tank

Figure 27. Schematic of fuel circuit for preliminary fuel screening

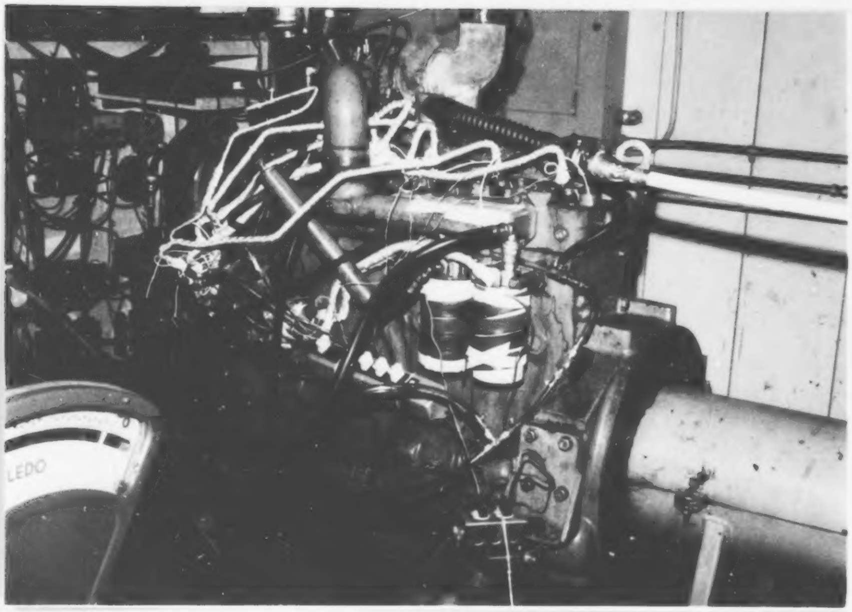


Figure 28. International Harvester DT-466B test engine modified for preliminary crude shale oil screening

The engine was operated on DF-2 through both the DF-2 and shale oil circuits in order to insure that proper operation was obtainable with either circuit and to establish baseline operating parameters. On DF-2, normal fuel temperatures were maintained during both 13-mode emissions testing and steady-state smoke measurement over 7 modes. Thirteen-mode composite gaseous emissions and modal smoke information from preliminary baseline operation are given in Table 22, along with a 7-mode composite of gaseous emissions based on individual 13-mode results. Gaseous emissions and engine parameters are given on a modal basis in Tables A-1, A-2 and A-3 of Appendix A. Gaseous emissions, smoke, and performance were satisfactory. Fuel temperature to the injection pump ranged from 96 to 101°F, while the temperature of the fuel approaching No. 1 injector ranged from 109 to 149°F.

The engine used in this program was supplied by EPA and had been used by EPA-Ann Arbor to explore the application of methanol as an alternative fuel. Following those experiments no apparent damage to the liners was noted on methanol, so the liners were honed and the pistons and rings originally supplied with engine were re-installed. The stock head was re-installed and new main bearings were used. The fuel injection pump was rebuilt and calibrated and the injectors were reconditioned as necessary.

Since only a brief break-in was performed prior to receiving the engine for use in this program, an informal borescope inspection of the cylinder liners was performed after preliminary operation on DF-2 for baseline purposes. All liners were "good" except on cylinder No. 4. Cylinder liner No. 4 had some bore

TABLE 22. PRELIMINARY EMISSION TEST DATA FOR THE INTERNATIONAL HARVESTER DT-466B ON DF-2 AND CRUDE SHALE OILS

Procedure or Condition	Measurement	Test Results by Fuel Used DF-2 EM-528-F	 Geokinetics EM-586-F	 Superior EM-584-F
13-Mode Composite	HC, g/bhp-hr	0.799	--	--
	CO, g/bhp-hr	2.411	--	--
	NO_x, g/bhp-hr	9.019	--	--
	BSFC, lb_m/bhp-hr	0.429	--	--
7-Mode Composite	HC, g/bhp-hr	0.778	0.944	1.541
	CO, g/bhp-hr	2.733	4.102	5.478
	NO_x, g/bhp-hr	9.042	8.227	7.649
	BSFC, lb_m/bhp-hr	0.433	0.428[a]	0.451[a]
1800 rpn, 2% load	smoke opacity, %	1.0	2.0	1.0
1800 rpm, 50% load	smoke opacity, %	3.5	3.5	3.5
1800 rpm, 100% load	smoke opacity, %	10.5	12.5	7.5
Idle (700 rpm)	smoke opacity, %	2.0	2.0	1.0
2600 rpm, 100% load	smoke opacity, %	9.0	10.0	11.0
2600 rpm, 50% load	smoke opacity, %	3.5	2.0	2.5
2600 rpm, 2% load	smoke opacity, %	2.0	1.0	2.0
2600 rpm, 100% load	power, hp	213	212	194
1800 rpm, 100% load	power, hp	152	149	144
all	pump fuel temp, °F	100±10	200^{+20}_{-10}	270^{+20}_{-40}
	injector fuel temp. °F	149 Max[b]	220±10	300±10

---

[a] based on DF-2 fuel measurements

[b] not controlled

polish (20%) on the thrust-side and some streaking (5%) on the anti-thrust side after approximately 2 hours of baseline operation on DF-2. The results of this initial borescope inspection are given in Table E-1 of Appendix E. Injector spray patterns and pressures were checked and found to be within specifications.

In preparation for operating the engine on the "best" candidate shale oil, a drum of filtered Geokinetics crude, EM-586-F, was heated to 150°F and circulated through the bypass leg of the "modified fuel system." The engine was brought to intermediate speed (1800 rpm) and 50 percent load (220 lb-ft), and stabilized on DF-2. Heating elements on the fuel filters, injection pump and injector lines were energized in order to bring the temperature of the DF-2 to about 160°F at the injection pump and about 210°F at the injectors. Once the engine's fuel system was up to temperature, the fuel system was switched to Geokinetics crude shale oil. The engine was operated for about 10 minutes, on shale oil supplied from the bulk drum. Then the fuel system was switched to shale oil supplied from the open container used for determining fuel consumption. The fuel pressure, measured after the secondary fuel filter, began to fall off, and the engine died. The engine could not be restarted. Both fuel filters were removed and found near empty. The fuel filters were filled with DF-2 and the hand-pump was used to purge the fuel system of shale oil. The fuel system was checked for leaks and none were found. The engine was restarted on DF-2 and the fuel system brought up to temperatures required for introduction of shale oil. Once again, after a short time on the Geokinetics shale oil supplied from the fuel measurement circuit (open container) the engine fuel pressure dropped off and the engine died. Following the same procedure as before, the engine was restarted on DF-2 and the system purged of shale oil.

For use on Geokinetics shale oil, system plumbing was such that the fuel was heated to about 200°F at the fuel filter assembly. The engine's fuel transfer pump drew the fuel through the first filter, then pushed it through the second filter and on to the injection pump. When the engine was operated on shale oil supplied from the bulk drum, the bypass was set so that the shale oil transfer pump would supply the engine fuel transfer pump with a positive 5 psig fuel pressure. When the engine was switched to the fuel measurement circuit on shale oil this supply pressure was not available and fuel pressure (measured after the secondary filter) would drop and the engine would die. A problem similar to vapor lock was suspected.

It was thought that this vapor lock problem on Geokinetics (EM-586-F) was caused by low-boiling-point hydrocarbons. Boiling point distributions for all six of the shale oils were given in Figure 19. Although EM-586-F has an initial boiling point near 315°F, it is conceivable that with this fuel near 200°F and under a vacuum (sufficient to draw it through the first filter), the actual initial boiling point was reduced to around 200°F. This could cause vapors to form in the first fuel filter and be pumped to the second fuel filter, causing the engine to "run out of fuel" (liquid).

Fuel measurement was dropped in favor of pursuing 7-mode engine operation for emissions, performance data, and smoke. The engine operated well on EM-586-F as long as the engine fuel transfer pump supply was under pressure (5 psig). After completing any operation on crude shale oil, the engine was brought to intermediate speed and 50 percent load, then switched to DF-2. Once the fuel supply and spillage lines were essentially running straight DF-2, the engine was stopped.

Surprisingly, the engine operated well on the Geokinetics crude shale oil heated to 200°F at the pump and 220°F at the injectors. Seven-mode composite gaseous emissions and steady-state smoke levels obtained on Geokinetics (EM-586-F) are given in Table 22. Detailed modal emissions and engine parameter data are given in Tables B-1 and B-2 of Appendix B. On Geokinetics, little difference in rated power was observed. No fuel flow measurements were obtained on Geokinetics. Results from the subsequent borescope inspection (Report No. 2, Table E-2 of Appendix E) indicated a further deterioration of cylinder liner No. 4, along with slight deterioration of cylinder liner No. 5 and No. 6 after about 2 hours of operation on Geokinetics. All cylinder liners had a "dull copper-colored finish," which was likely due to a thin coating of shale oil.

In preparation for running the "worst" candidate crude shale oil, filtered Superior (EM-584-F), the engine's fuel system was modified again. This shale material had to be heated to about 320°F to obtain a viscosity of 3 centistokes. The engine's transfer pump was refitted to draw fuel from the supply (at 150°F) then push the shale oil through a fuel-to-exhaust heat exchanger, through the engine's two fuel filters, and on to the injection pump. It was anticipated that this fuel system would be suitable to allow for fuel flow measurement without creating problems with vapor lock.

The engine and fuel system (with new filters) were brought up to temperature (fuel to pump, 240°F; fuel to injectors, 260°F), then switched to the filtered Superior crude shale oil (bulk drum at 150°F). Fuel temperatures increased to the desired levels (fuel to pump, 270°F; fuel to the injectors, 320°F), and the engine operated satisfactorily with about 10 psig pressure supplied to the engine's fuel transfer pump. Efforts to obtain fuel flow measurement were made, but due to problems in handling the fuel return spillage from the injectors and injection pump at nearly 300°F, it was not possible. The spillage returning to the open container used for fuel measurement tended to foam and overflow. This foaming was attributed to the 0.5 percent water content of the Superior shale oil, flashing to steam.

Seven-mode composite gaseous emissions and smoke levels obtained on the Superior crude shale oil (EM-584-F) are given in Table 22. Modal emissions and engine parameters are given in Tables C-1 and C-2 of Appendix C. The maximum power dropped 9 percent, from 213 hp observed on DF-2 to 194 hp on Superior. Idle speed was initially near 750 rpm, but after operation on shale oil the idle speed was near 650 rpm. Results from borescope inspection (Report No. 3, given as Table E-3) indicated further deterioration of cylinder liner No. 4 and other liners after about 3 hours on the Superior shale oil. The liners had a silver color, as noted after operation on DF-2 (Borescope Report No. 1), and the deposits appeared to be less pronounced than noted after operation on Geokinetics. Since deterioration of the engines' liners was noted prior to operation on shale oil, it was difficult to attribute the increases in wear to the use of the shale oils; and it was decided that the program should be continued without servicing the engine at this point. It was felt that enough fuel handling and engine operation experience had been accumulated so that no more preliminary work was necessary.

Examining the preliminary data presented in Table 22, 7-mode composite HC and CO emissions increased when shale crudes were burned. HC emissions increased by 21 percent with Geokinetics and nearly doubled with the Superior, as compared to those obtained on DF-2. Emissions levels of CO increased 50 percent with Geokinetics and nearly doubled with Superior over the level obtained on DF-2. NO_x emissions decreased, even though both shale oils contained some fuel-bound nitrogen. Relative to the levels of NO_x obtained on DF-2, NO_x emissions decreased by 9 percent on Geokinetics and by 15 percent on Superior. The Superior crude shale oil contained 1.59 percent nitrogen; whereas the Geokinetics contained 1.12 percent nitrogen.

Changes in smoke levels measured for the 7 modes of steady-state operation on shale oils were relatively minor. Smoke opacities for the maximum torque and maximum power conditions increased slightly on Geokinetics. On Superior, the smoke opacity was slightly lower at the maximum torque condition, but higher at the maximum power condition. An odor of raw shale oil was apparent in the vicinity of the exhaust plume.

After completing the preliminary screening on DF-2 (EM-528-F), the "best," and the "worst" candidate shale oils, the engine was moved to the transient-capable test facility, Cell 1. Figure 29 shows the engine, overall fuel system, and overall exhaust system as set-up for transient operation. Figure 30 shows the left side of the engine with the various heated and insulated lines, fuel filters, and injection pump as set-up for transient operation. The fuel handling system, illustrated in Figure 31, was upgraded by incorporating a regulated fuel supply pressure feed to the engine's transfer pump when drawing from any fuel source. In addition to the fuel-to-exhaust heat exchanger, a fuel spillage-to-cooling water heat exchanger was included to keep the return spillage from exceeding 180°F. The engine was operated on DF-2 from all sources of fuel supply to assure that there were no problems in the various fuel circuits.

The DT-466B test engine was mapped as prescribed by the transient test procedure using DF-2. The results of the torque map are given in Table A-4 in Appendix A. The resulting transient cycle command had a total transient cycle work of 12.86 hp-hr, and was used for transient testing of both the baseline DF-2 and the crude shale oils. Over the map, the maximum torque was 454 lb-ft at 2100 rpm, and the maximum power was 206 hp at 2600 rpm. The idle speed was 650 rpm, down from the initial reading of near 750 rpm taken during set-up on DF-2 for preliminary fuel screening.

Before transient testing for emissions characterization, the engine was operated over the transient cycle on DF-2 to assure that the fuel handling hardware was capable of supporting the engine through the transient cycle and to make necessary adjustments to the dynamometer controls to meet the prescribed statistical criteria for engine operation.

Since cold-start transient operation on the crude shale oils was impractical, it was decided that emissions samples were to be obtained only for

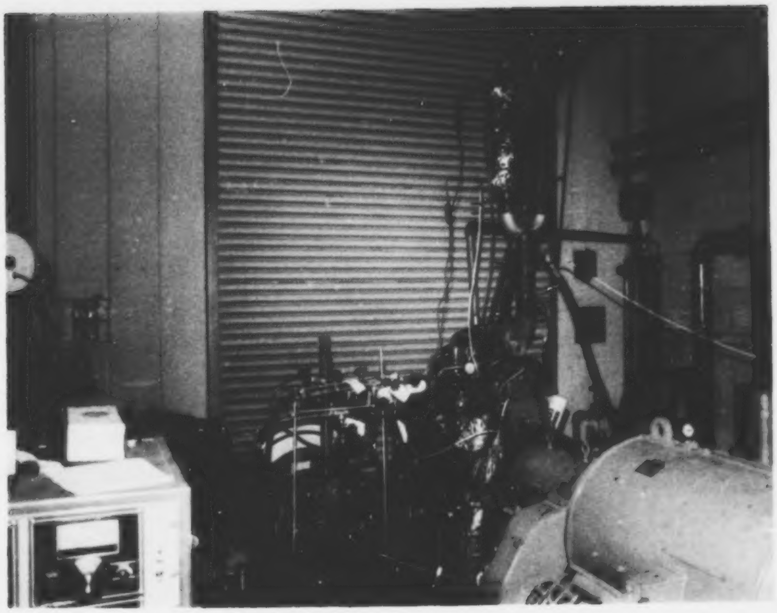


Figure 29. International Harvester DT-466B set-up for transient testing on crude shale oils

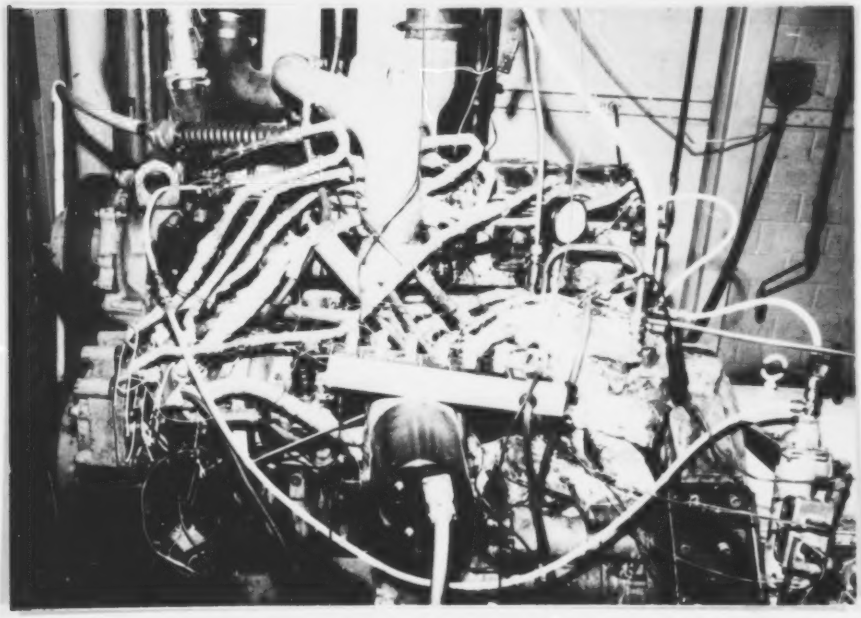
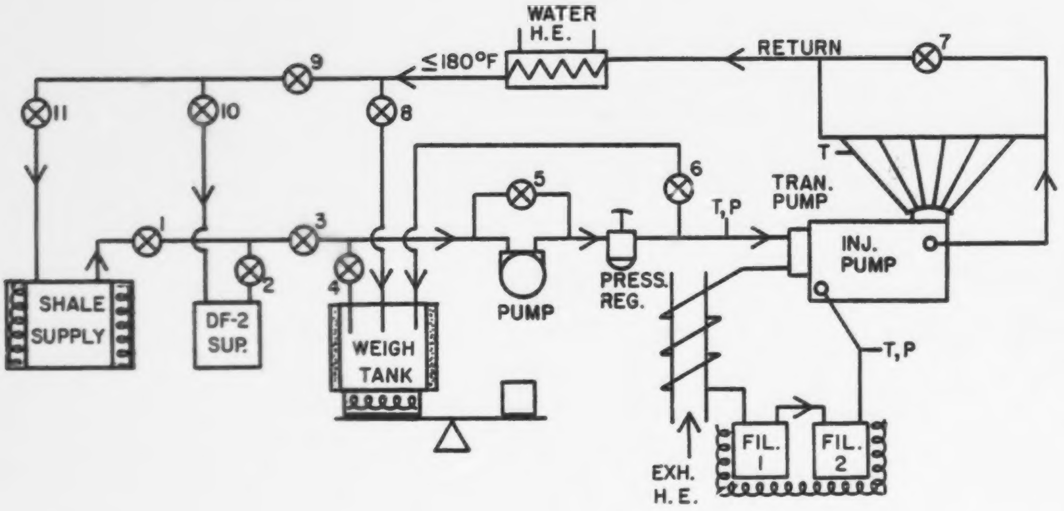


Figure 30. Left side view of DT-466B with heated fuel system for operation on crude shale oils


WATER
H.E.
≤180°F
RETURN
7
9
11
10
8
6
5
1
3
2
4
T
TRAN.
PUMP
T,P
INJ.
PUMP
SHALE
SUPPLY
DF-2
SUP.
WEIGH
TANK
PUMP
PRESS.
REG.
T,P
EXH.
H.E.
FIL.
1
FIL.
2

Valve Identification

1. Shale Oil Supply
2. DF-2 Supply
3. Bulk Supply
4. Weigh Tank Supply
5. Pump Recirculation
6. Weigh Tank Fill
7. Injector Spillage Purge
8. Spillage Return, Weigh Tank
9. Spillage Return, Bulk
10. Spillage Return, DF-2
11. Spillage Return, Shale Oil

Figure 31. Schematic of fuel system used during transient emissions characterization of the DT-466B on DF-2 and crude shale oils

hot-start transient operation. In addition, it was not practical to hot-start the engine on crude shale oil because of the potential problems of developing hot or cold spots in the fuel system. For emissions characterization on DF-2, the engine was brought up to temperature, allowed to idle for about 3 minutes, and then started on the transient cycle. Sampling from the single-dilution CVS commenced with the start of engine control by the transient cycle command. The relatively large single dilution CVS is shown in Figure 32 along with sample carts used to acquire samples for unregulated emissions. On DF-2 (EM-528-F), emissions samples were taken over three consecutive cycles, run back-to-back with no engine-off soak time between cycles. This procedure allowed sufficient accumulation of particulates on various filter media to insure that enough loading was obtained for characterization of the total particulate. Gaseous HC emissions were monitored and integrated over the three runs of this transient sequence. In addition, four sample bags (one for each segment) for other gaseous emissions were taken over each of the three hot-start transient cycles. Most samples taken for unregulated emissions on DF-2 were accumulated over the three consecutive runs. Following the initial transient sequence (Test 1-Run 1, Run 2, and Run 3), the exhaust was rerouted, sample media were renewed, and a replicate transient sequence was performed (Test 1-Run 4, Run 5, and Run 6).

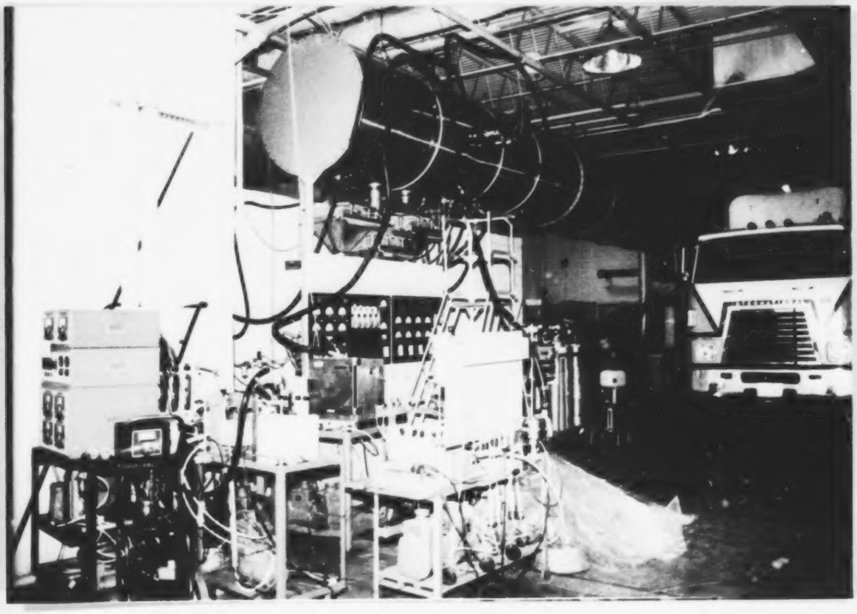


Figure 32. Single dilution CVS tunnel and control panel

Following the second transient sequence, a 13-mode FTP for regulated gaseous emissions was performed. Fuel measurement on DF-2 was accomplished using a Flo-tron. Smoke opacity was determined over the FTP for smoke, and over 13 modes of steady-state operation on DF-2. A maximum power of 198 hp with 82.8 lb/hr of DF-2 was observed during the 13-mode test.

After completing planned emissions characterization on DF-2, the engine's injectors were pulled, and a borescope inspection was performed. Figure 33 shows the deposits on the tips of all six injectors from operation on DF-2. These injectors had been cleaned prior to baseline transient testing. The wet oily appearance was due to diesel fuel wetting the injectors during removal. The borescope inspection (Report No. 4, Table E-4) indicated that cylinder liner No. 4 was scuffed around 70 percent of the liner circumference, and that the other cylinder liners showed signs of deterioration. It was thought at the time that the liner scuffing might be contributing to the reduction in maximum power, from 213 to 198 hp on DF-2; but a decrease in maximum power fuel flow also occurred. This observation led to conjecture that the injection pump was beginning to deteriorate.

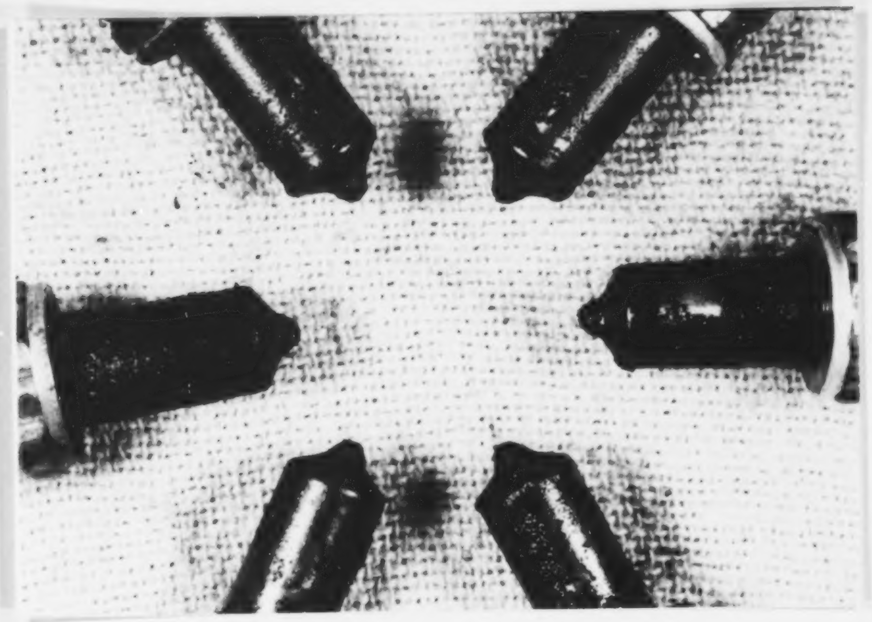


Figure 33. Injector nozzle tips after operation on DF-2 (EM-528-F)

Emphasis was placed on obtaining emissions samples from transient operation on the Superior shale oil (EM-584-F), which was deemed "worst case" crude shale oil. The engine and fuel system were brought up to near shale oil operating temperatures while running intermediate speed and 50 percent load. All operation was conducted with 10 psig fuel pressure to the engine's transfer pump. The engine's fuel supply was switched over to the Superior shale oil, and the fuel-to-exhaust heat exchanger adjusted to obtain 220°F at the injection pump and 320°F at the injectors. The return spillage was cooled to near 180°F by the spillage-to-cooling water heat exchanger. The engine was operated at maximum power for about 5 minutes, then allowed to idle for about 3 minutes prior to the start of the transient cycle test. After the 3 minute idle, the exhaust was diverted from the outside exhaust stack to the CVS, and sampling under transient cycle control was begun.

Based on adjustments made to sample flow rates during an experimental transient test, a single run for record was found sufficient to provide the necessary samples for various particulate analyses. The raw exhaust was diverted from the CVS to the outside exhaust stack when the transient cycle (Test 2, Run 1) was completed. The engine was not shut off due to potential problems of restart associated with the high pour point of the shale oil. All sample media were renewed while the engine was operated on shale oil at intermediate speed and 50 percent load. Following about 3 minutes of idle, the exhaust was diverted to the CVS and sampling over the transient test cycle (Test 2, Run 2) was repeated. The exhaust was diverted to the outside exhaust stack upon completion of the transient test, and the engine was switched over the DF-2 and shutdown.

On the next day, the engine was brought up to speed and temperature on DF-2, and switched to the Superior shale oil for 13-mode emissions. Fuel measurements were made using the weight balance method, and were sufficiently accurate for processing 13-mode emissions data. A maximum power of 187.1 hp with 77.4 lb/hr of the Superior shale oil was observed during the 13-mode test. After completing planned smoke opacity measurements, the engine was shut down on DF-2 and the injectors were pulled for a borescope inspection. Figure 34 shows the nozzle tips of the six injectors.

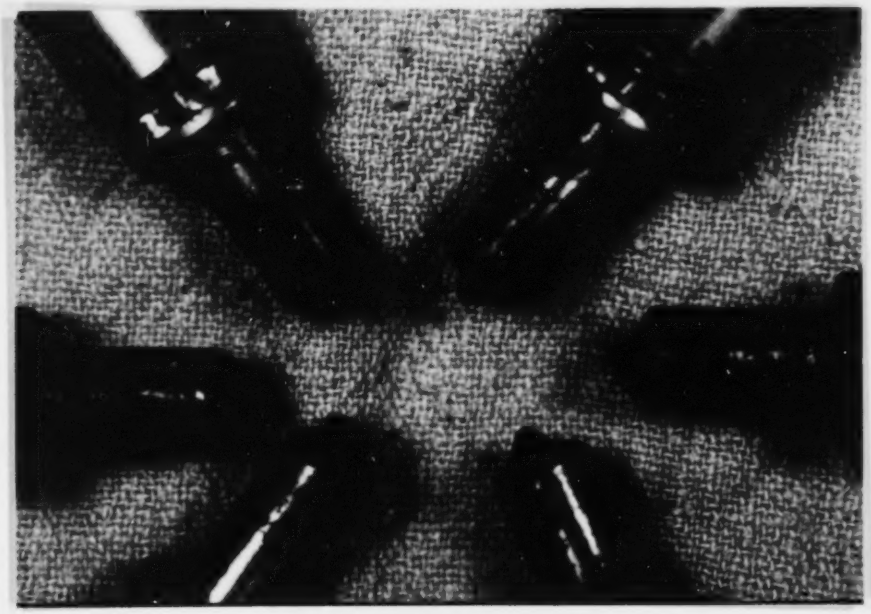


Figure 34. Injector nozzle tips after operation on Superior crude shale oil (EM-584-F)

All injectors had a relatively large-deposit of hard, dry material and some showed signs of having a tunnel-like passage formed around the nozzle holes. It should be noted that these deposits were left after the engine was operated briefly on DF-2 in order to purge the engine's fuel system. This system purge generally took from 20 to 30 minutes of operation at intermediate speed and 50 percent load on DF-2. Approximately eight hours of engine operation had been accumulated on the Superior crude shale oil. The borescope inspection (Report No. 5, Table E-5) indicated a worsening of the engine's overall condition. The liners generally had a dull appearance, and the tops of the pistons were dull black with a note of varnish color. The metallic surface of the pistons were still visible. The injectors were cleaned (externally) and reinstalled.

Having completed emissions testing of the "worst case" material, it was considered reasonable to expect that transient testing on the "best" shale oil material would be relatively straight forward. The fuel filters were replaced, and the engine was started on DF-2, then switched to heated Geokinetics following the procedure established on the previous shale oil runs. The engine operated for about 15 to 20 minutes on the heated Geokinetics shale oil, then fuel pressure began to fall off, and the engine died. The fuel circuit was checked, and no problems could be found. Only a slight pressure could be obtained by using the hand pump. It appeared that the fuel filters had plugged, so both the primary and secondary filters were replaced. The engine was restarted on DF-2, brought to temperature, and switched to the Geokinetics shale oil. Once again, the fuel pressure began to drop off, but this time the engine was switched back to DF-2. The fuel pressure stabilized on DF-2, so the engine was purged of remaining shale oil and shutdown.

Both fuel filters were removed and cut open for examination, as shown in Figure 35. The primary filter was dark but the fiber of the filter medium was visible. On the secondary filter, the fiber filter media was completely covered in black oily product. Evidently, some polymerization occurred during storage of the filtered Geokinetics material. The entire drum of filtered Geokinetics was filtered again, using the filtration system described earlier in Figure 16.

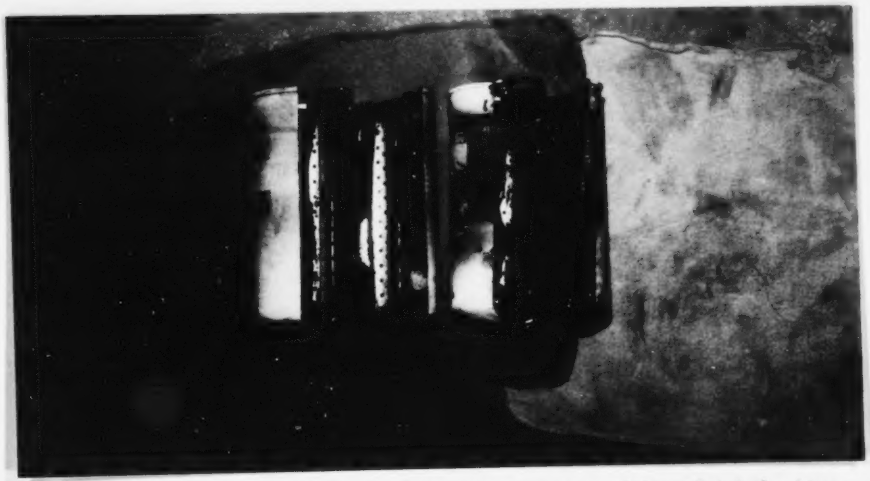


Figure 35. Primary filter (left) and secondary filter (right) after fouling on filtered Geokinetics crude shale oil (EM-586-F).

The engine was started on DF-2 and switched over to re-filtered Geokinetics, and no further problems occurred. Two transient test runs (Test 3, Run 1 and Test 3, Run 2) were made as with the Superior crude shale oil. A borescope inspection was made after completing the 13-mode gaseous emissions test and the smoke test. A maximum power of 196 hp with 85.7 lb/hr of Geokinetics was observed during the 13-mode test.

The borescope inspection revealed that not only was liner scuffing continuing to worsen, but small holes or depressions were beginning to form on the top of the piston crowns. The engine had accumulated about 12 hours of operation since the last inspection. The deposits on the piston tops were black to dry-gray in color, and the cylinder walls had a copper-colored finish (as noted earlier after the preliminary fuel screening on Geokinetics). In addition, the injectors had a very heavy build-up of deposits, such that tunnels had formed around each of the nozzle spray holes. Figure 36 shows all six nozzle tips, while Figure 37 shows a closeup of the formation representative of all the injectors. The injectors were cleaned, and new fuel filters were installed.

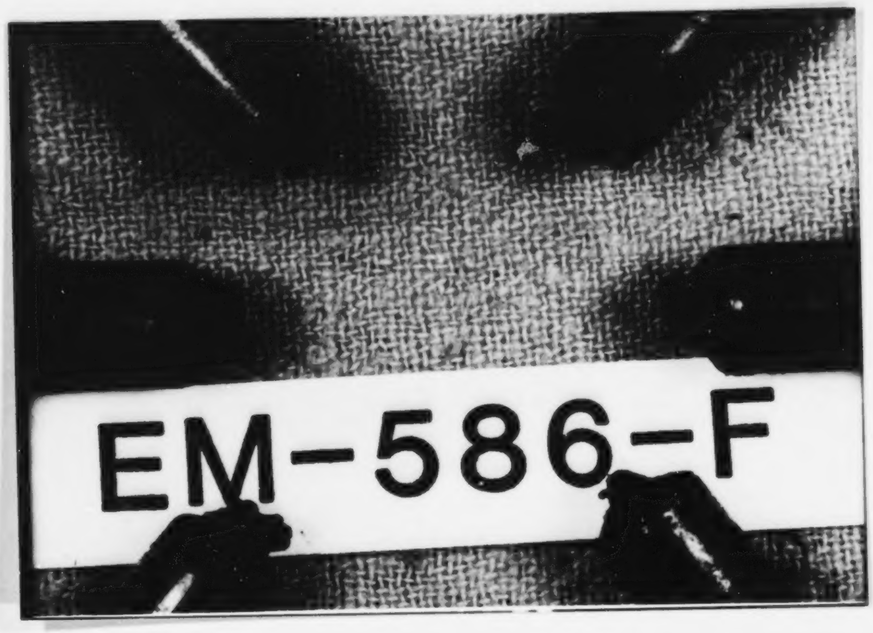


Figure 36. Injection nozzle tips after operation on Geokinetics crude shale oil (EM-596-F)

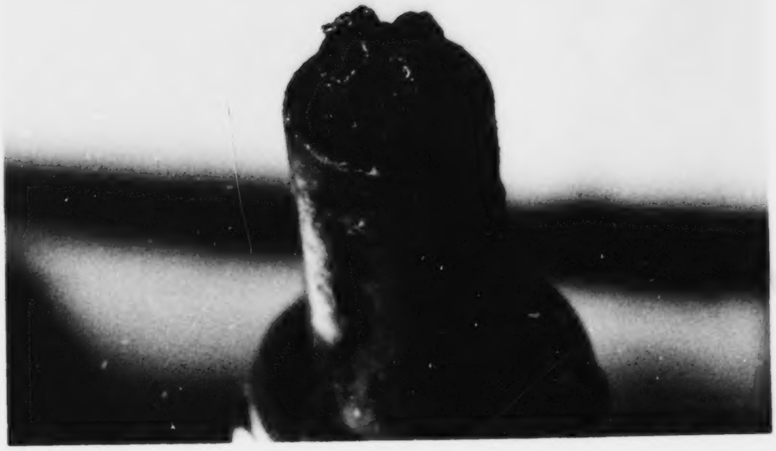


Figure 37. Close-up of deposit formation on nozzle tip after operation on Geokinetics crude shale oil (EM-586-F)

Another crude shale oil of interest was the Paraho DOE (EM-585-F). This shale oil was considered as "next to the worst case" fuel. The engine and fuel system was brought up to temperature on DF-2 and switched over to the heated Paraho DOE. This shale oil was heated to about 240°F at the inlet to the injection pump, and about 280°F at the injectors. No problems were encountered during testing on the Paraho DOE, and two transient test runs (Test 4-Run 1 and Test 4-Run 2) were completed on the first day of operation. Thirteen-mode gaseous emissions and smoke testing were completed on the second day of operation. A maximum power of 189.1 hp with 82.5 lb/hr of Paraho DOE was observed during the 13-mode test.

After about seven hours of engine operation on the Paraho DOE shale oil, the borescope inspection (Report No. 7, Table E-7) indicated that liner scuffing generally appeared to have stabilized, or at least further damage to the liners was indistinguishable from earlier damage. The indentations at the tops of the piston crowns had become more defined. Deposits on the tops of the pistons appeared as "dark tan" and "sandy." In addition, all liners had a dull copper color. Deposits on the injector tips are shown in Figure 38, and were similar to those already noted with use of the Geokinetics shale oil. However, the tunnel formation appeared to be even longer than noted before. The injectors were cleaned and the fuel filters replaced. The engine was operated for one hour at various speeds and loads on DF-2. The engine was removed from the test area. The head was removed for inspection of the pistons, and the fuel injection pump was sent out for examination.

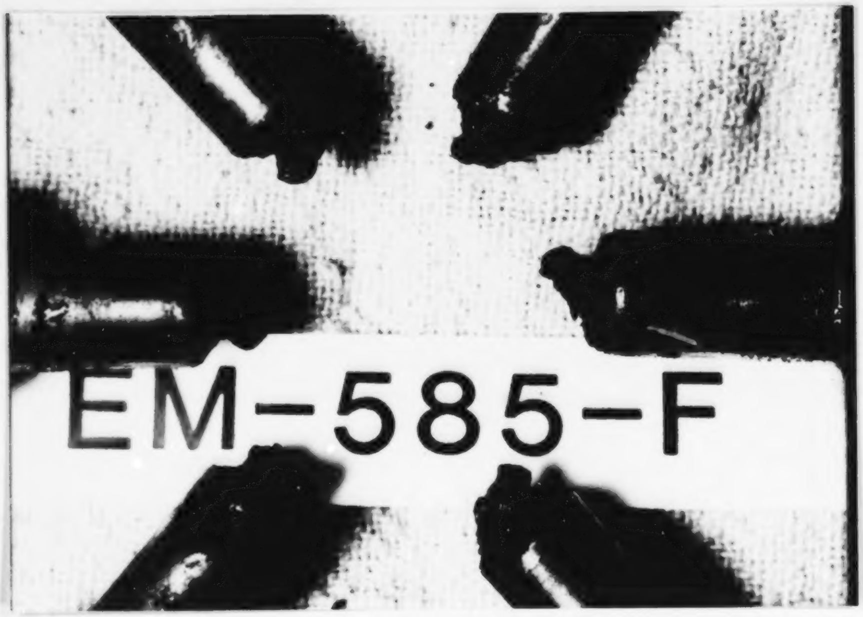


Figure 38. Injector nozzle tips after operation on Paraho DOE crude shale oil (EM-585-F)

B. Gaseous Emissions

The term "gaseous emissions" usually refers to HC, CO, and NO_x, which are emissions regulated by EPA. This section presents the results of emissions measurements which include not only these regulated gaseous emissions, but also selected individual hydrocarbons, ammonia, cyanide, aldehydes, and phenols. Odor intensity, which has been shown to correlate with the presence of some of these gas phase emissions, is also presented.

1. HC, CO, and NO_x

These regulated pollutants were measured over the 1979 13-mode FTP as well as the 1984 Transient FTP. In 1984, the transient test procedure was optional in lieu of the 13-mode test procedure. In 1985, the transient test procedure becomes mandatory, and in 1986 the proposed transient test procedure would include particulate measurement and regulation. For perspective, some of the heavy-duty diesel standards for 1979 and beyond are listed on the following page.

Model Year	FTP	Regulated Emissions, g/hp-hr HC	CO	NO_x	Particulate
1979	13-Mode	1.5	25.	10.0	None
	13-Mode (opt.)	--	25.	5.0	None
1984	13-mode[b]	0.5[c]	15.5[d]	9.0	None
	Transient[b]	1.3	15.5[d]	10.7	None
1985	Transient	1.3	15.5[d]	10.7[e]	None[e]

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[a] Federal Smoke Regulations apply

[b] Manufacturer may certify by either procedure

[c] Subject to revision to 1.0 g/hp-hr

[d] CO measurement requirements for heavy-duty diesels may be waived after 1983

[e] EPA plans to propose revising the NO_x standard and to issue a particulate standard for a future model year

As described earlier, detailed emissions characterization was performed after the initial fuel screening portion of the program was completed. The International Harvester DT-466B test engine was operated over the 1984 Transient test cycle (hot-start only). The results from the average of replicate hot-start transient tests on DF-2 and on each of the three crude shale oils is given in Table 23. Detailed results from individual runs are given in

TABLE 23. REGULATED EMISSIONS SUMMARY FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Test Fuel	Regulated Emissions, g/kW-hr (g/hp-hr) HC	CO	NO_x	Part.	Cycle BSFC[a,b] kg/kW-hr (lb/hp-hr)	Cycle Work kW-hr (hp-hr)
DF-2[c]	1.27	3.12	11.05	0.95	0.271	9.35
EM-528-F	(0.95)	(2.33)	(8.24)	(0.71)	(0.445)	(12.54)
Superior[d]	2.15	6.66	10.82	3.11	0.282	9.30
EM-584-F	(1.60)	(4.97)	(8.06)	(2.32)	(0.465)	(12.47)
Geokinetics[d]	2.17	4.51	10.57	2.09	0.274	9.24
EM-586-F	(1.62)	(3.36)	(7.88)	(1.56)	(0.450)	(12.39)
Paraho DOE[d]	2.29	5.66	11.77	2.86	0.271	9.40
EM-585-F	(1.71)	(4.22)	(8.78)	(2.13)	(0.446)	(12.61)

---

[a] based on carbon balance

[b] fuel carbon fraction: EM-528-F, 0.869; EM-584-F, 0.841; EM-586-F, 0.851; EM-585-F, 0.849

[c] average based on 6 hot-start runs

[d] average based on 2 hot-start runs

Appendices A, B, C, and D for testing on DF-2, Geokinetics, Superior, and Paraho DOE, respectively. The baseline values, established on DF-2, represent the average results of six individual hot-start transient tests. Results from these individual runs are tabulated in Table A-7 and the corresponding computer printouts from the individual runs are given in Tables A-8 through A-13 of Appendix A. The emissions values from operation of the Superior crude oil given (run after emissions testing on DF-2) are given in Table 23 and represent the average value of the separate hot-start transient tests tabulated in Table C-5. The individual computer printouts from these two tests are given in Tables C-6 and C-7 of Appendix C. Similarly, the average emission levels obtained over two hot-starts on Geokinetics, and on Paraho DOE are given in Table 17. Detailed results from operation on Geokinetics are given in Tables B-5, B-6, and B-7 of Appendix B. Detailed results from the two transient tests run on Paraho DOE are given in Tables D-3, D-4, and D-5.

The hot-start transient gaseous emissions of HC, CO, and NO_x from operation on DF-2 were all below the 1984-1985 regulated emission levels. Operation on the three crude shale oils caused hydrocarbons to increase by 68 to 80 percent. Emissions of CO increased by a factor of 1.8 and 2.1 on both the Paraho DOE and the Superior. CO increased by 44 percent on the Geokinetics. Emissions of NO_x were relatively unchanged. On the Superior and Geokinetics, levels of NO_x emissions were slightly lower (2 and 4 percent, respectively). On the Paraho DOE, the NO_x increased slightly (6.5 percent). All three shale oils contained "fuel bound" nitrogen, and were expected to show increases in NO_x emissions. The increased HC and CO emissions imply, however, that combustion of the shale oils was not optimized with respect to changing the timing to account for potential changes in ignition delay; and perhaps this lack of optimization is part of the reason why higher levels of NO_x emissions were not noted on the crude shale oils.

Not much change in the BSFC was noted on any of the crude shale oils, although the trend was toward higher BSFC. Total particulate, which will be discussed in a later section, increased by a factor of 3.3 on the Superior, 3.0 on the Paraho DOE, and 2.2 on the Geokinetics as compared to DF-2. Cycle work over all hot-start transient testing was essentially the same on all fuels. No problems were encountered in meeting the statistical criteria for transient testing, even though the engine was not re-mapped on each fuel.

In addition to the 7-mode steady-state emission test work performed during the fuel screening, a 13-mode FTP was also conducted on each fuel after completing the transient testing. Results from the single 13-mode test on each fuel are summarized in Table 24. Detailed results of each test are given in the Appendices corresponding to each of the fuels. The 13-mode test results, along with additional engine parameters, are given in Tables A-5 and A-6 for DF-2, Tables B-3 and B-4 for Geokinetics, Tables C-3 and C-4 for Superior, and Tables D-1 and D-2 for the Paraho DOE.

TABLE 24. GASEOUS EMISSIONS SUMMARY FROM 13-MODE OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

		13-Mode			
		Emissions, g/kW-hr, (g/hp-hr)			BSFC kg/kW-hr (lb/hp-hr)
Test Fuel	Test No.	HC	CO	NO_x	
DF-2[a] EM-528-F	01-01	1.26 (0.94)	3.02 (2.25)	11.38 (8.49)	0.271[a] (0.446)
Superior[b] EM-584-F	02-01	1.32 (0.98)	6.80 (5.07)	10.33 (7.70)	0.274 (0.450)
Geokinetics[b] EM-586-F	03-01	1.13 (0.84)	4.41 (3.29)	11.16 (8.32)	0.282 (0.463)
Paraho DOE[a] EM-585-F	04-01	1.22 (0.91)	6.92 (4.41)	10.61 (7.91)	0.277[a] (0.456)

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[a] based on measured fuel flow

[b] based on fuel flow measurement from run on DF-2

Thirteen-mode composite emissions of HC obtained on the three crude shale oils were about the same as obtained on DF-2. Generally, increases in HC emissions during idle and light loads (2 percent loads) were off-set by slight reductions during higher power operation. On Geokinetics, HC from the 2 percent load and rated speed condition were lower than obtained on DF-2. As observed from transient test results, 13-mode composite CO emissions on Superior and Paraho DOE were similar and about 2.1 times those obtained on DF-2. Most of the increase in CO was observed below the 75 percent load level, and was particularly noticeable during idle (idle CO increased from 30 g/hr on DF-2 to about 220 g/hr on Superior and Paraho DOE). On Geokinetics, the 46 percent increase in 13-mode composite CO was mostly due to increases in CO emissions over the idle, 2 percent and 25 percent load conditions. In addition, little change in the 13-mode composite NO_x emission level was noted on Geokinetics for which slight increases in some modes were off-set by slight decreases in NO_x emissions over other modes. Composite NO_x emission levels on the Superior and Paraho DOE were also lower than on the DF-2, generally due to lower NO_x emissions during the higher load conditions, especially full load operation.

Over both the 13-mode and transient testing, BSFC tended to be higher on all three shale oils compared to DF-2. It was surprising that the BSFC only increased by an average of 3.8 percent over the steady-state procedure and about 1.9 percent over the transient procedure on the shale oils, considering that the engine was not optimized for their use. Recall that the fuel consumption over the 13-mode FTP is based on measured fuel usage, whereas BSFC over the transient FTP is based on carbon balance. Although the heat of combustion for the three crude shale oils was not determined in this program, Reference 12 indicated that the gross heating value for crude shale oils ranges from 18,330 to 18,680 BTU/lb. This is similar to or slightly below the heating value of No. 2 diesel fuel.

2. Selected Individual Hydrocarbons

Some individual hydrocarbons (IHC) were determined from dilute exhaust samples and processed by chromatographic techniques to separate methane, ethylene, ethane, acetylene, propylene, propane, benzene and toluene. High molecular weight hydrocarbons were not measured. In order to obtain proportional samples over the transient cycle, dilute exhaust samples were collected from the main tunnel of the CVS.

The averages of results obtained from replicate determinations of selected individual hydrocarbons are given in Table 25. Detailed results from separate analyses are given in Appendix Table A-14 for DF-2, Table B-8 for Geokinetics, Table C-8 for Superior, and Table D-6 for Paraho DOE.

With the exception of methane emissions noted on DF-2, repeatability of replicate tests was very good. From Table 25, neither propane nor toluene was found over transient operation on any of the four fuels run in the DT-466B. Small concentrations of benzene were noted during hot-start transient operation on Superior and Paraho DOE crude shale oils. Ethylene was the most prevalent hydrocarbon species for all the fuels tested, followed by propylene, methane, acetylene, and ethane. Total IHC emission levels were obtained by simply adding the emission levels of the individual species for a given fuel. The largest total was obtained on Superior, followed by Paraho DOE, then Geokinetics, and finally DF-2. Of the totals, ethylene and propylene constituted about 57 and 24 percent on the average, respectively. Acetylene, which has been linked to particulate growth rate by GM researchers,(23) was lowest for the DT-466B when on Geokinetics, slightly higher on DF-2, and highest on Superior and Paraho DOE. Acetylene accounted for between 3 and 5 percent of the "total" individual hydrocarbons detected.

3. Aldehydes

Aldehydes were determined by the liquid chromatograph DNPH procedure. Dilute samples were taken over hot-start transient operation. The average of replicate determinations are given in Table 26. Detailed results from analysis of the replicate samples are given in the Appendices, Table A-15 for DF-2, Table B-9 for Geokinetics, Table C-9 for Superior, and Table D-7 for Paraho DOE. Fairly good repeatability was noted for all samples except for the determination of formaldehyde while on Superior (Table C-9). The second run on Superior yielded almost 3 times the level obtained for the first run. Of the various species, formaldehyde was most prevalent; followed by acetaldehyde, then acrolein, acetone, isobutyraldehyde and MEK as a group; followed by lesser levels of the remaining aldehydes. The total aldehyde emission level of the DT-466B, obtained by adding the emission levels of the various species, was lowest on the DF-2, then followed by (in order of increasing emissions) Superior, Geokinetics, and Paraho DOE. The total aldehydes from the three crude shale oils were generally about 2 times the level obtained on DF-2.

TABLE 25. SUMMARY OF INDIVIDUAL HYDROCARBONS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Individual Species of Hydrocarbon	DF-2 EM-528-F[a]			Superior EM-584-F[a]			Geokinetics EM-586-F[a]			Paraho DOE EM-585-F[a]		
	mg/ test	mg/ kW-hr	mg/ kg fuel	mg/ test	mg/ kW-hr	mg/ kg fuel	mg/ test	mg/ kW-hr	mg/ kg fuel	mg/ test	mg/ kW-hr	mg/ kg fuel
Methane	290	31	220	550	60	220	120	13	46	240	25	93
Ethylene	830	88	330	1700	180	670	1200	140	490	1500	160	600
Ethane	6.3	0.67	2.5	85	9.1	34	12	1.4	4.9	67	7.2	26
Acetylene	60	6.4	24	120	13	48	49	5.3	19	120	12	46
Propane	0	0	0	0	0	0	0	0	0	0	0	0
Propylene	370	40	150	610	66	240	510	55	200	620	66	240
Benzene	0	0	0	160	17	62	0	0	0	53	5.7	21
Toluene	0	0	0	0	0	0	0	0	0	0	0	0
Total	1500	170	610	3200	350	1300	1900	210	760	2600	280	1000

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[a] Average of two samples

TABLE 26. SUMMARY OF ALDEHYDES FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Individual Species of Aldehyde	DF-2 EM-528-F[a,b]			Superior EM-584-F[a,c]			Geokinetics EM-586-F[a,c]			Paraho DOE EM-585-F[a,c]		
	mg/ test	mg/ kW-hr	mg/ kg fuel	mg/ test	mg/ kW-hr	mg/ kg fuel	mg/ test	mg/ kW-hr	mg/ kg fuel	mg/ test	mg/ kW-hr	mg/ kg fuel
Formaldehyde	570	61	220	910	98	350	1100	120	440	1300	130	490
Acetaldehyde	460	49	180	720	77	280	940	100	370	950	100	370
Acrolein	180	19	70	250	27	96	420	46	170	430	46	170
Acetone	220	23	87	510	54	200	500	54	200	230	25	91
Propionaldehyde	11	1.2	4.3	72	7.8	28	130	14	50	180	19	71
Crotonaldehyde	2.5	0.26	0.96	75	8.1	29	160	18	65	170	18	67
Isobutyraldehyde & Methylethylketone	100	11	40	270	30	110	120	13	48	240	26	94
Benzaldehyde	26	2.8	10	66	7.1	26	120	13	47	150	16	59
Hexanaldehyde	35	3.8	14	85	9.1	33	140	15	54	190	21	76
Total	1600	170	630	2900	320	1200	3600	390	1400	3800	410	1500

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[a] Average of analysis of two samples

[b] Each sample was obtained over 3 consecutive runs

[c] Sample was obtained over 1 run

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TABLE 27. SUMMARY OF PHENOLS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Phenols	DF-2 EM-528-F[a]			Superior EM-584-F[b]			Geokinetics EM-586-F[b]			Paraho DOE EM-585-F		
	mg/ test	mg/ kW-hr	mg/ kg fuel	mg/ test	mg/ kW-hr	mg/ kg fuel	mg/ test	mg/ kW-hr	mg/ kg fuel	mg/ test	mg/ kW-hr	m/g kg fuel
Phenol	0	0	0	0	0	0	0	0	0	0	0	0
Salicylaldehyde	0	0	0	0	0	0	0	0	0	49	5.2	19
M- & P-cresol	0	0	0	0	0	0	0	0	0	0	0	0
Five[c]	19	2.0	7.4	0	0	0	95	10	37	24	2.7	9.5
TNPPH[d]	0	0	0	0	0	0	0	0	0	0	0	0
TR235[e]	0	0	0	20	2.2	8.1	27	2.9	11	0	0	0
T2356[f]	0	0	0	0	0	0	0	0	0	0	0	0
Total	19	2.0	7.4	20	2.2	8.1	122	13	48	73	7.9	29

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[a] Values based on analysis of single sample

[b] Average values from analysis of two samples

[c] p-ethylphenol, 2-isopropylphenol, 2,3-xylenol, 3,5-xylenol, 2,4,6-trimethylphenol

[d] 2-n-propylphenol

[e] 2,3,5-trimethylphenol

[f] 2,3,5,6-tetramethylphenol

4. Phenols

Phenols were determined from dilute exhaust samples taken over transient operation. The averages of two separate determinations are given in Table 21. The detection of individual phenols in dilute exhaust is quite variable. Results from analysis of the separate samples are given in the Appendices, Table A-16 for DF-2, Table B-10 for Geokinetics, Table C-10 for Superior, and Table D-8 for Paraho DOE. Only one sample from operation on DF-2 was suitable for analysis, and replicate samples taken during operation on Geokinetics and Superior indicated no phenols above the level of background. Hence, values in Table 27 for Geokinetics and Superior were averaged with zero, reducing the level obtained from a single run by half. Similarly, on Paraho DOE a phenol species noted over one run did not appear over the repeat run, so values for Paraho DOE shown in Table 27, represent half the level obtained for a single run. Overall, all the levels of phenols were very low and near the level of minimum detection. "Total" phenol emission levels were lowest on DF-2, followed by Superior, Paraho DOE and Geokinetics.

5. Cyanide

Total cyanide, including cyanide compounds (HCN) and cyanogen (C_2N_2), was determined from dilute samples obtained over hot-start transient operation. Table 28 summarizes the average of results obtained from replicate sample analysis for total cyanide. Repeatability was quite good except for the determination on Geokinetics. Total cyanide was hardly present on DF-2. The exhaust emission levels obtained on Geokinetics, and more so on Superior and Paraho DOE, could possibly cause problems in confined areas. A possible mechanism leading to cyanide emission may be formation during the in-cylinder combustion process due to fuel-bound nitrogen, or it may be due to the "liberation" of cyanide occurring in the fuel in the form of substituted groups (i.e., nitriles). Recall that the Superior and Paraho DOE contained 1.59 and 1.82 percent nitrogen, respectively, and that Geokinetics contained 1.12 percent nitrogen.

TABLE 28. SUMMARY OF CYANIDE EMISSIONS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Test Fuel	Test No.	Run No.	mg/test	mg/kW-hr	mg/kg fuel
DF-2	1	1-3	9.4	1.0	3.8
EM-528-F	1	4-6	7.6	0.81	3.0
	Average		8.5	0.91	3.4
Superior	2	1	220	23	87
EM-584-F	2	2	280	30	110
	Average		250	27	98
Geokinetics	3	1	140	16	57
EM-586-F	3	2	37	4.0	15
	Average		91	9.8	36
Paraho DOE	4	1	240	26	94
EM-585-F	4	2	260	28	100
	Average		250	27	98

6. Ammonia

Ammonia was determined from dilute exhaust samples taken over the hot-start transient. A summary of the results is given in Table 29. Repeatability from one run to the next was not as good as desired. Considering the resulting averages, only operation on Geokinetics showed an increase in ammonia emissions over DF-2.

TABLE 29. SUMMARY OF AMMONIA EMISSIONS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Test Fuel	Test No.	Run No.	mg/test	mg/kW-hr	mg/kg fuel
DF-2	1	1-3	400	42	160
EM-528-F	1	4-6	960	100	380
	Average		680	72	270
Superior	2	1	590	64	240
EM-584-F	2	2	---[a]	---[a]	---[a]
	Average		590	64	240
Geokinetics	3	1	1100	120	440
EM-586-F	3	2	730	78	290
	Average		930	100	370
Paraho DOE	4	1	420	44	160
EM-585-F	4	2	960	100	380
	Average		690	74	270

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[a] Unrepresentative sample

7. Odor-TIA

Total intensity of aroma (TIA) was determined from DOAS analysis of dilute exhaust samples taken over hot-start transient operation. The averages of replicate determinations are given in Table 30. Results from individual analyses are given in the Appendices, Table A-17 for DF-2, Table B-11 for Geokinetics, Table C-11 for Superior, and Table D-9 for Paraho DOE. Repeatability from run to run was generally good. The TIA on the basis of liquid column aromatics (LCA) was generally around 1.36 for the three crude shale oils as compared to 1.00 for the DF-2. On the basis of liquid column oxygenates (LCO), the TIA was about 2.38 for the three crude shale oils as compared to 1.26 for the DF-2. A significant increase in the intensity of odor over that obtained on DF-2 was indicated by either method when the crude shale oil materials were used.

TABLE 30. SUMMARY OF TIA BY DOAS[a] FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Test Fuel	LCA µg/ℓ	TIA[b]	LCO µg/ℓ	TIA[c]
DF-2 EM-528-F	7.11	1.00	1.98	1.26
Superior EM-584-F	22.50	1.35	38.43	2.53
Geokinetics EM-586-F	21.96	1.34	20.81	2.32
Paraho DOE EM-585-F	25.64	1.39	19.65	2.28

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[a] These measurements were based on DOAS standard corresponding for use of No. 2 diesel fuel. Samples were taken from exhaust diluted approximately 12:1 for the overall transient cycle. Values represent average results from two test samples.

[b] TIA based on liquid column aromatics (LCA) by:
$TIA = 0.4 + 0.7 \log_{10} (LCA)$

[c] TIA based on liquid column oxygenates (LCO) by:
$TIA = 1 + \log_{10} (LCO)$, (TIA by LCO preferred)

In addition, the general odor noted around the area of the engine's exhaust stack was similar to that in the area of shale oil handling. That is, the odor of raw crude shale oil was also associated with the exhaust plume of the engine.

C. Particulate Emissions

Although heavy-duty diesel particulate emissions are not currently regulated (but will be in the future), they have been measured for some time and have been recognized as a potential problem in the application of diesel engines. Particulate emissions were studied in this program for purposes of comparison. In order to determine particulate emission rates and to characterize the total particulate, samples were collected on several filter media for a variety of analyses which included total mass, elemental analysis, and organic extractables. Particulate samples were always taken from the dilute exhaust using a CVS.

1. Smoke

Smoke and particulate emissions are related, smoke level being a measure of the visible portion of particulate matter. Changes in particulate emissions may be indicated by corresponding changes in smoke opacity, if the levels are high enough. Black smoke is indicative of mostly carbonaceous types of particulate material, whereas, white smoke indicates substantial quantities of unburned fuel materials (and is usually associated with cold start up).

Smoke opacity was determined using an end-of-stack PHS smokemeter on a 4 inch diameter exhaust stack. Table 31 summarizes the smoke opacity data obtained over both steady-state modal operation and smoke FTP operation. Detailed results from smoke FTP chart readings are given in the Appendices, Table A-18 for DF-2, Table B-12 for Geokinetics, Table C-12 for Superior, and Table D-10 for Paraho DOE.

On DF-2, the FTP smoke opacities were well under the current statutory limits. When the engine was operated on the Geokinetics crude, maximum power and maximum torque steady-state smoke levels were (surprisingly) near, or lower than those obtained on DF-2. Similarly, on Superior and Paraho DOE crudes, not much difference in maximum torque smoke, and only a relatively small change in maximum power smoke opacity were observed as compared to results on DF-2. The greatest change in steady-state smoke opacity was noted for the light loads and idle conditions, especially during prolonged light load or idle conditions on Superior and Paraho DOE shale oil. On these two shale oil crudes, prolonged light load operation caused the smoke opacity to increase substantially with time, changing from a low level of black smoke to dense white smoke.

Over the smoke FTP, which contains a five minute idle, the "peak" smoke was primarily due to the puff of smoke occurring during the 1st acceleration along with the early portion of the 2nd acceleration. The "acceleration" smoke from this engine included the smoke from all three accelerations and also included the initial peak just described. The "lug" portion was determined after almost 50 seconds of maximum power operation, as specified by the procedure. The smoke from the first and second accelerations, while on the Superior and Paraho materials was mostly dense white smoke. Hence, the "peak" smoke operation and the "acceleration" smoke opacities were relatively high on both the Superior and Paraho shale oils. There was not such a noticeable difference over the "lug" portion of the test, because the engine was operated at maximum power for a time (50-60 seconds) sufficient to exhaust the unburned fuel accumulated in the engine exhaust system. Examining the results from operation on Geokinetics indicated the same phenomena as described above, but to a lesser extent.

2. Total Particulate

Total particulate was determined over hot-start transient operation of the DT-466B in replicate. Results from the individual tests are given in Table 32 along with the average levels of total particulate. More details associated with sample flows and filter efficiencies are given in the computer printouts for the individual test results, presented in the Appendices corresponding to the various fuels. On DF-2, total particulate emissions over transient operation were 0.95 g/kW-hr, or 0.71 g/hp-hr. On all three crude shale oils, the total particulate emission levels increased by about a factor of 2.8 (average). Since the transient cycle contains a substantial fraction of idle operation interrupted by moderate load operation, it appears that the nearly

TABLE 31. SUMMARY OF SMOKE OPACITY FROM THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Federal Transient Smoke Cycle Opacity, %

Test Fuel	Accel.	Lug	Peak
DF-2 EM-528-F	11.5	8.7	14.9
Superior EM-584-F	34.5[a]	10.7	69.7
Geokinetics EM-586-F	20.9[b]	6.3	24.4
Paraho DOE EM-585-F	32.0	7.8	69.3

13-Mode			Smoke Opacity, %, by Fuel			
Mode	RPM	Power, %	DF-2 EM-528-F	Superior EM-584-F	Geokinetics EM-586-F	Paraho DOE EM-585-F
1	650	-	0.2	1.0[c,d]	0.5	2.5
2	1800	2	0.1	1.2	1.0	11.0[e]
3	1800	25	0.5	1.2	1.1	2.8
4	1800	50	2.7	2.6	2.0	3.2
5	1800	75	4.2	6.0	3.0	5.0
6	1800	100	8.2	8.5	6.5	8.0
7	650	-	0.2	1.0	0.8	0.5
8	2600	100	7.0	11.0	7.1	8.0
9	2600	75	3.0	4.5	2.0	2.9
10	2600	50	1.8	3.9	1.0	2.2
11	2600	25	2.2	3.5	1.2	3.0
12	2600	2	1.5	2.0	0.8	1.5
13	650	-	0.5	1.0[f]	0.5	2.5

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[a] White smoke, heavy white to brown-black puff during 2nd and 3rd accelerations.

[b] Short puff of white smoke during accelerations

[c] White smoke

[d] Puffy-not stable

[e] Following almost 10 minutes of idle

[f] The longer idle is held, the higher white smoke intensity becomes; smoke level reached 40% opacity after about 10 minutes

threefold increase in total particulate emissions on the Superior and Paraho DOE crude shale oils followed the trend noted for the smoke test. That is substantial emission of unburned or partially burned fuel was emitted as white smoke over the smoke FTP after periods of engine idle. On Geokinetics, the total particulate emissions increased by a factor of 2.2, likely due also to increased emissions of unburned or partially burned fuel during the light loads of the transient cycle. These unburned fuel species in total particulate are generally accounted for in the soluble organic fraction of the total particulate.

TABLE 32. TOTAL PARTICULATE AND SOLUBLE ORGANIC FRACTION FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Test Fuel	Test No.	Run No.	Total Particulate g/kW-hr	Total Particulate g/kg fuel	Percent SOF, %	Soluble Organic Fraction g /kW-hr	Soluble Organic Fraction g /kg fuel
DF-2	1	1-3	0.93	3.49	41.1	0.38	1.43
EM-528-F	1	4-6	0.97	3.54	39.9	0.39	1.41
	Avg		0.95	3.52	40.5	0.38	1.43
Superior	2	1	3.18	11.43	58.9	1.87	6.73
EM-584-F	2	2	3.04	10.61	60.4	1.84	6.41
	Avg		3.11	11.02	59.6	1.85	6.57
Geokinetics	3	1	2.16	7.87	60.3	1.30	4.75
EM-586-F	3	2	2.01	7.35	59.3	1.19	4.36
	Avg		2.08	7.61	59.8	1.25	4.55
Paraho DOE	4	1	2.79	10.27	64.5	1.80	6.62
EM-585-F	4	2	2.92	10.81	63.0	1.84	6.81
	Avg		2.86	10.54	63.8	1.82	6.72

3. Soluble Organics

The soluble organic fraction (SOF) of the total particulate was determined by extraction of relatively large particulate samples. The results of these analyses are also given in Table 32. As mentioned earlier, the SOF is generally attributed to unburned or partially burned fuel, and lubricating oil. On DF-2, the SOF accounted for 40 percent of the total particulate with emissions of 0.38 g SOF/kW-hr. On the three crude shale oils, SOF accounted for about 60 percent of the total particulate emissions with an average emission of 1.6 g SOF/kW-hr.

On the Superior and Paraho DOE shale oils, SOF emissions averaged 1.8 g SOF/kW-hr, or 6.6 g SOF/kg fuel over the transient cycle, some 4.7 times the level obtained on DF-2. On a fuel basis, this implies that 0.66 percent of the fuel consumed by the engine was emitted as organics (aerosols and gases) and collected on the filter media as part of the total particulate. On Geokinetics, the level of SOF emissions was lower than for the other shale crudes (about 1.25 g/kW-hr), but still 3.3 times that obtained on DF-2.

4. Sulfate

Sulfate was determined from samples of total particulate collected on 47 mm Fluoropore filter media during the transient testing, processed by the BCA method. Results of sulfate analysis are summarized in Table 33. Since the sulfate originates from the sulfur contained in the fuel, sulfate emissions were computed in terms of mg/kg fuel and percent of fuel sulfur converted to sulfate ($SO_4^=$).

TABLE 33. SULFATE EMISSION SUMMARY FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Test Fuel	Test No.	Run No.	Sulfate Emissions mg/test	Sulfate Emissions mg/kW-hr	Sulfate Emissions mg/kg fuel	% of Fuel S in $SO_4^=$
DF-2	1	1-3	310	33.2	124	1.79
EM-528-F	1	4-6	322	34.3	126	1.83
	Average		316	33.8	125	1.81
Superior	2	1	2350	253	939	3.75
EM-584-F	2	2	1350	146	524	2.10
	Average		1850	199	732	2.93
Geokinetics	3	1	1100	119	432	2.16
EM-586-F	3	2	1100	120	438	2.19
	Average		1100	119	435	2.18
Paraho DOE	4	1	1210	128	472	2.22
EM-585-F	4	2	1320	140	519	2.44
	Average		1260	134	496	2.33

On DF-2, containing 0.22 percent sulfur, sulfate emissions were 33.8 mg/kW-hr, representing about 1.8 percent conversion of fuel sulfur to sulfate. On all three crude shale oils , sulfate emission levels were much higher. On Geokinetics, containing 0.67 percent sulfur, sulfate emissions were 119 mg/kW-hr, representing 2.2 percent fuel sulfur conversion to sulfate. Similarly, on Superior and Paraho, which contained 0.84 and 0.71 percent sulfur, the sulfate emissions increased over baseline to 199 and 134 mg/kW-hr, respectively. The percent of fuel sulfur converted to sulfate was 2.93 percent for Superior and 2.33 percent for Paraho.

Although it is logical to expect that high sulfur content fuel would produce greater sulfate emission levels, it was unexpected that the percent of fuel sulfur converted to sulfate would also increase. The higher conversion occurred even though emissions of HC, CO, NO_x and SOF indicated that combustion quality on shale oil was lower than on DF-2. Some of the increased sulfate emissions may be due to a positive interference of unburned fuel on the determination of sulfate.(5) Other reasons may be that the shale oils might contain metallic "salts," which could include oxides of sulfur. Also, the crude shale oils likely contain various concentrations of organic sulfur compounds and about 1 percent oxygen, which may combine more readily to form sulfur oxides.

5. Elemental Composition

Elemental analysis of the total particulate required two particulate samples. The carbon, hydrogen, and nitrogen contents of the total particulate were determined using oxidation techniques on particulate samples collected on glass fiber filter media. Sulfur and metal content were determined from particulate samples collected on Teflon membrane (Fluoropore) filter media using x-ray fluorescence techniques. The carbon, hydrogen, and nitrogen were determined by Galbraith Laboratories, and the sulfur and metals were determined by EPA-RTP.

A summary of elemental analysis is given in Table 34. Average carbon content was highest for the DF-2 at 87.2 percent. For the three crudes, the average carbon content of the total particulate ranged from 79.3 to 83.5 percent. Average hydrogen content was lowest for the DF-2 at 7.8 percent, and it ranged from 9.6 to 9.9 for the three crude shale oils. Computed H/C mole ratios of the total particulate yielded 1.06 for the DF-2, 1.36 for Superior, and 1.48 for both the Geokinetics and Paraho. These values of H/C mole ratio of the total particulate indicate that the particulate from the three crude shale oils tended to be more oily (or contain more organics) than that from operation on DF-2. This result supports the findings described for SOF emissions.

Average nitrogen content of the total particulate was relatively high for the DF-2, and was even higher for the particulate samples from the Geokinetics and Paraho DOE, which were just over 5 percent nitrogen. The comparatively low nitrogen level of 2.05 percent obtained for the total particulate from operation on Superior is puzzling, and could not be confirmed by a replicate analysis.

Sulfur content of the particulate was lowest for DF-2 at 1.2 percent whereas for the shale oils, the percent sulfur in the particulate ranged from 1.7 to 2.3 percent. Particulate from operation on DF-2 contained very little iron, (0.08 percent). On Geokinetics, iron was 0.8 percent whereas on Paraho DOE and Superior the iron was about 1 percent of the total particulate. Although the crude shale oils contained small amounts of arsenic, no arsenic was noted in the total particulate samples above the detection limit of 0.045 percent. Elements of Ca, Zn, and P (totaling about 0.2 percent) were also noted for the total particulate from each of the fuels and are likely due to the engine oil.

6. Boiling Point Distribution

A high-temperature GC-simulated boiling point distribution with internal standard (C_9-C_{11}) was conducted on the SOF from the total particulate collected over hot-start transient operation on DF-2 and the crude shale oils. Chromatograms from analysis of replicate samples of SOF are given in Figure 39. The peak data from the internal standard, which has a retention time between 10 and 15 minutes, was omitted for the sake of simplicity. The

TABLE 34. SUMMARY OF ELEMENTAL ANALYSIS OF TOTAL PARTICULATE FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Individual Elements % wt.	DF-2, EM-528-F			Superior, EM-584-F			Geokinetics, EM-586-F			Paraho DOE, EM-585-F			Detection Limit
	Runs 1-3	Runs 4-6	Avg.	Run 1	Run 2	Avg.	Run 1	Run 2	Avg.	Run 1	Run 2	Avg.	
C	87.2	87.3	87.2	82.5	84.4	83.5	76.5	83.6	80.0	75.7	83.0	79.3	a
H	7.95	7.78	7.78	8.98	10.1	9.6	9.49	10.4	9.9	9.11	10.6	9.8	a
N	4.22	5.48	4.85	2.05	a	2.05	4.81	6.50	5.65	4.23	6.25	5.24	a
S	1.79	1.57	1.19	1.29	2.17	1.73	2.43	1.72	2.08	2.33	a	2.33	0.009
Al	b	c	c	b	b	b	b	b	b	b	a	b	0.002
As	b	b	b	b	b	b	b	b	b	b	a	b	0.045
Ba	b	b	b	b	b	b	b	b	b	b	a	b	0.013
Br	c	c	c	c	c	c	c	c	c	c	a	c	0.093
Ca	0.129	0.112	0.12	0.107	0.114	0.11	0.187	0.101	0.14	0.148	a	0.15	0.003
Cd	b	b	b	b	b	b	b	b	b	b	a	b	0.009
Cl	0.006	0.011	0.01	c	0.026	0.01	0.025	c	0.01	0.022	a	0.01	0.006
Co	b	b	b	b	c	c	c	c	c	b	a	b	0.028
Cu	0.033	0.055	0.04	c	c	c	0.144	0.119	0.13	c	a	b	0.031
Cr	c	b	c	c	b	c	0.219	c	0.11	c	a	c	0.058
Fe	0.089	0.066	0.08	0.930	1.279	1.11	0.968	0.645	0.81	1.002	a	1.00	0.030
Hg	b	b	b	b	b	b	b	b	b	b	a	b	0.145
K	c	0.009	c	0.014	c	0.07	c	b	c	b	a	b	0.003
Mg	0.141	0.087	0.11	0.045	0.037	0.04	c	c	c	c	a	c	0.012
Mn	b	b	b	b	b	b	b	b	b	b	a	b	0.038
Na	b	b	b	b	b	b	b	b	b	b	a	b	0.092
Ni	c	c	c	c	0.098	0.05	0.142	0.142	0.14	0.113	a	0.11	0.027
P	0.100	0.084	0.09	0.035	0.051	0.04	0.065	0.038	0.05	0.048	a	0.05	0.009
Pb	b	b	b	b	b	b	b	b	b	b	a	b	0.259
Pt	b	b	b	b	b	b	b	b	b	b	a	b	0.115
Sb	b	b	b	b	b	b	b	b	b	b	a	b	0.009
Se	b	b	b	b	b	b	b	b	b	b	a	b	0.055
Si	0.013	0.015	0.01	c	0.049	0.02	0.047	c	0.02	c	a	c	0.012
Sn	b	b	b	b	b	b	b	b	b	b	a	b	0.022
Sr	c	c	c	c	c	c	c	c	c	c	a	c	0.015
Ti	b	0.005	c	b	b	b	0.023	c	0.01	b	a	b	0.004
V	b	b	b	b	b	b	b	b	b	b	a	b	0.020
Zn	0.092	0.150	0.12	c	0.134	0.07	0.141	0.121	0.13	0.239	a	0.24	0.032

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[a] No data

[b] Concentration below the detection limit

[c] Element was detected but was below the level of quantitation

[d] Detection limit is dependent on particulate loading, three values are based on a loading of 1 mg (which was the range of loading for samples submitted for x-ray)

vertical scale units of "mV" and "slice units" are for data manipulation by computer only, and can not be translated into meaningful units (Figure 39). Results were also plotted on a distillation chart in Figure 40. Boiling point temperatures of several HC's with various carbon numbers have been designated by "NC-XX" on Figure 40 for comparative purposes.

From Figure 39, the SOF from operation on DF-2 was noticeably different than that derived from operation on the three crude shale oils. It should be noted that the chromatograms shown in Figure 39 represent varying portions of the resulting SOF, that is, there was significant variation in the amount of "residue" as shown in Figure 40. The residue contains relatively large molecules of organic soluble substances which are not boiled off at the simulated distillation temperature of 600°C (or 1110°F), such as asphaltenes and tar-like residuals.

For SOF from operation on DF-2, the residue was 24 percent; whereas on Geokinetics, it was 35 percent; on the Superior, it was 41 percent; and on Paraho DOE, 46 percent. This order of increasing residue is in the same rank order as that occurring for the fuels themselves in Figure 21. From Figures 39 and 40, along with Table 16, SOF from operation on DF-2 and Geokinetics had a 50 percent boiling point retention time of 26 minutes, similar to a paraffinic hydrocarbon of approximately 32 to 36 carbon atoms. The 50 percent boiling point for the SOF from operation on Superior and Paraho DOE had retention times of 28 and 29 minutes, respectively, similar to hydrocarbons of approximately 40 to 44 carbon atoms.

7. Elemental Composition of SOF

The carbon, hydrogen, and nitrogen contents of the SOF from transient operation on DF-2 and the three crude shale oils are given in Table 35. The percent of carbon in the SOF was greatest from operation on DF-2 at 85 percent. Carbon content for both the Geokinetics- and Paraho DOE-derived SOF were about the same, near 82 percent. SOF from operation on Superior had the lowest carbon content with 80 percent. A similar order was noted for the hydrogen content. The SOF derived from operation on DF-2 had the greatest percent hydrogen content of about 12 percent, while the SOF from operation on the three crude shale oils contained about 11 percent hydrogen.

The H/C mole ratios from these SOF carbon and hydrogen data are as follows: SOF from DF-2, 1.73; SOF from Superior, 1.57; SOF from Geokinetics, 1.65; and SOF from Paraho DOE, 1.62. The values correlate quite well with the H/C mole ratios of the various fuels which were: DF-2, 1.78; Superior, 1.58; Geokinetics, 1.68; and Paraho DOE, 1.59. It is not clear that the correlation is due to a physical relationship, but it is interesting that the correlation occurred at all.

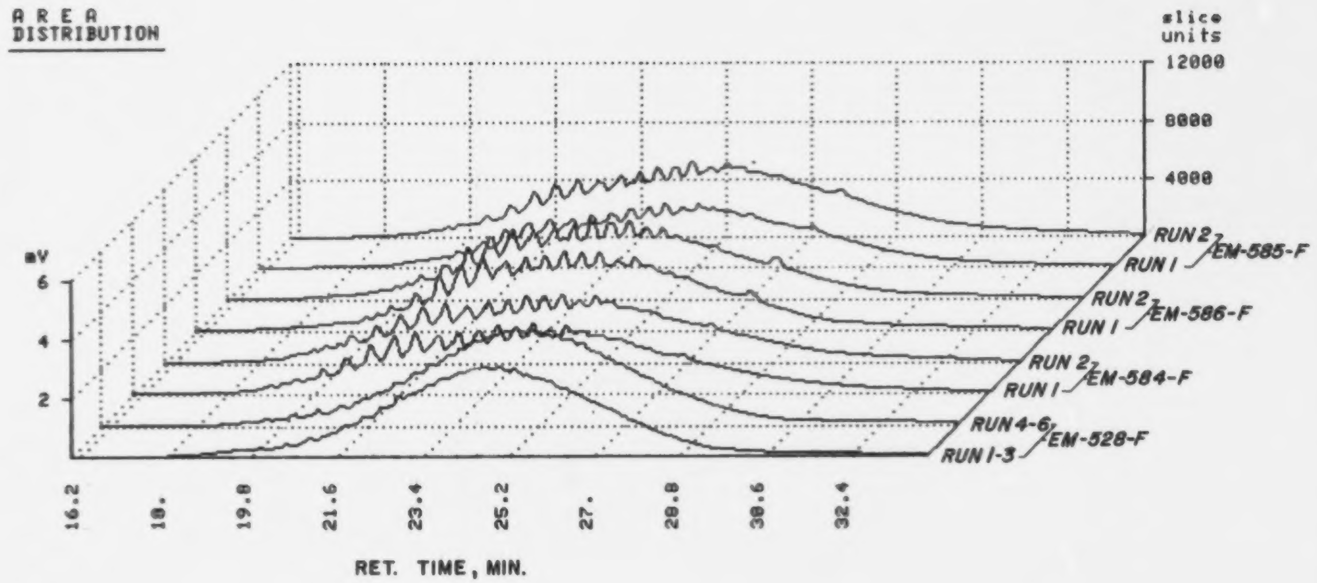

Figure 39. Area distribution of boiling point data obtained from SOF over hot-start transient operation of the IH DT-466B on DF-2 and crude shale oils

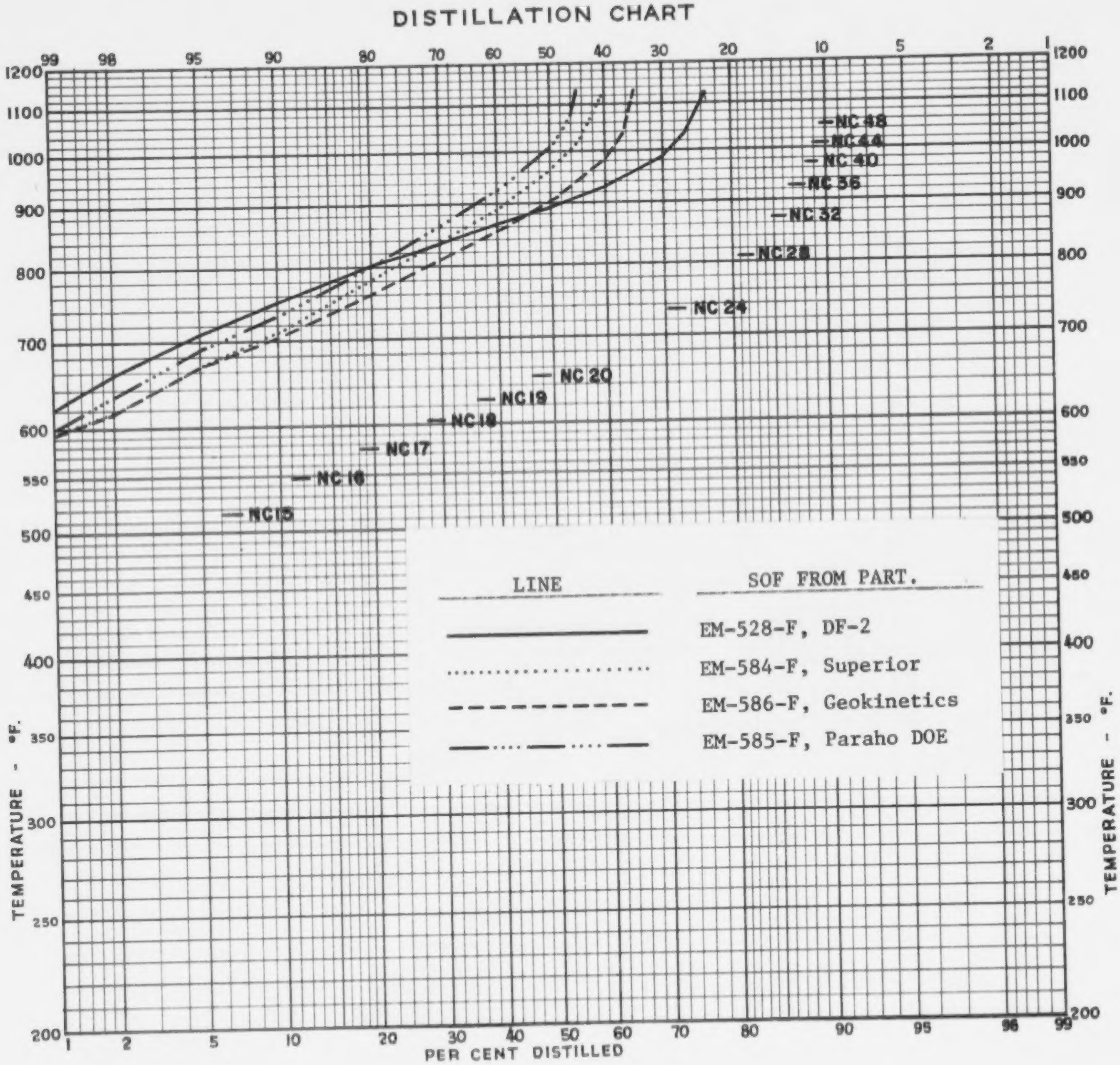

Figure 40. Boiling point distribution of SOF from hot-start transient operation of IH DT-466B on DF-2 and crude shale oils

TABLE 35. SUMMARY OF ELEMENTAL ANALYSIS OF SOF FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Test Fuel	Test No.	Run No.	Individual Elements, % by wt.		
			C	H	N
DF-2	1	1-3	84.91	12.07	0.15
EM-528-F	1	4-6	84.74	12.54	0.15
	Average		84.8	12.3	0.15
Superior	2	1	83.63	12.00	0.76
EM-584-F	2	2	76.11	9.00	0.74
	Average		79.9	10.5	0.75
Geokinetics	3	1	79.39	10.11	0.95
EM-586-F	3	2	84.11	12.42	0.98
	Average		81.8	11.3	0.96
Paraho DOE	4	1	77.55	9.73	1.02
EM-585-F	4	2	85.67	12.48	0.95
	Average		81.6	11.1	0.99

Nitrogen content of the SOF derived from operation on DF-2, at 0.15 percent, was substantially higher than the level noted in the fuel at 0.01 percent. For the SOF derived from Superior, the nitrogen content was 0.75; whereas, for the fuel it was 1.59 percent. SOF derived from operation on Geokinetics had a nitrogen content of 0.96, whereas for the fuel it was 1.12. Nitrogen content of the SOF derived from operation on Paraho DOE was 0.99 percent; whereas, for the fuel, is was 1.82 percent. As a group, SOF samples from operation on crude shale oils contained much more nitrogen than the sample of SOF from operation on DF-2. Scatter was present in the observed relationship between SOF nitrogen and fuel nitrogen; so the mechanism generating the SOF nitrogen is not yet well understood. Examination of samples from different operating conditions on the same "fuel," known to produce different amounts of raw or partially-burned fuel in the exhaust, might shed some additional light on this matter.

8. Selected PAH Content of SOF

Replicate samples of SOF, derived from repeat hot-start transient testing on DF-2 and three crude shale oils were analyzed for various polynuclear aromatic hydrocarbons (PAH). Results of these individual analyses are given in Table 36 along with the average concentration and computed brake and fuel specific emission levels. On DF-2, the brake specific emission of 1-nitropyrene was quite low at 0.96 μg/kW-hr. Brake specific emissions of 1-nitropyrene were slightly greater on Geokinetics and Paraho DOE with the greatest emission level being noted on Superior, which had a brake specific emission of 10 μg/kW-hr.

TABLE 36. SUMMARY OF 1-NITROPYRENE AND PAH OF SOF FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

PAH	Run	Units	DF-2 EM-528-F	Superior EM-584-F	Geokinetics EM-586-F	Paraho DOE EM-585-F
1-Nitropyrene	1	μg/g SOF	2.3	6.8	2.6	3.6
	2	μg/g SOF	2.7	4.5	3.4	3.7
	Avg	μg/g SOF	2.5	5.7	3.0	3.5
	Avg	μg/kW-hr	0.96	10	3.7	6.3
	Avg	μg/kg fuel	3.6	37	13	23
Pyrene	1	μg/g SOF	48	415	311	250
	2	μg/g SOF	101	244	252	392
	Avg	μg/g SOF	75	330	280	320
	Avg	μg/kW-hr	28	610	350	580
	Avg	μg/kg fuel	110	2200	1300	2200
Chrysene	1	μg/g SOF	26	97	129	77
	2	μg/g SOF	59	34	117	66
	Avg	μg/g SOF	42	66	120	72
	Avg	μg/kW-hr	16	120	150	130
	Avg	μg/kg fuel	61	430	560	480
Benz(a)anthracene	1	μg/g SOF	11	80	76	47
	2	μg/g SOF	5.0	28	70	44
	Avg	μg/g SOF	8.0	54	73	46
	Avg	μg/kW-hr	3.0	100	91	83
	Avg	μg/kg fuel	11	350	330	306
Benzo(e)pyrene	1	μg/g SOF	11	30	59	47
	2	μg/g SOF	9.3	14	34	22
	Avg	μg/g SOF	10	22	46	34
	Avg	μg/kW-hr	3.9	41	58	63
	Avg	μg/kg fuel	15	140	210	230
Benzo(a)pyrene	1	μg/g SOF	7.8	41	27	32
	2	μg/g SOF	8.0	24	21	23
	Avg	μg/g SOF	7.9	32	24	28
	Avg	μg/kW-hr	3.0	60	30	50
	Avg	μg/kg fuel	11	210	110	180
Total of Measured PAH		μg/g SOF	150	510	550	500
		μg/kW-hr	55	940	680	920
		μg/kg fuel	210	3300	2500	3400

Of the various PAHs identified, pyrene was predominant followed by chrysene, benz(a)anthracene, then benzo(e)pyrene, and benzo(a)pyrene. On a brake specific basis, SOF from operation on Superior generally contained the highest levels of PAHs, followed by SOF from operation on Paraho DOE, then Geokinetics. Emissions of all PAHs from operation on the three crude shale oils were substantially greater than when DF-2 was used.

9. Bioassay of SOF

Samples of SOF obtained from hot-start transient operation on DF-2 and the three crude shale oils were submitted for bioassay using the Ames test procedure. These samples were tested over five strains: TA97A, TA98, TA100, TA102, and TA98NR, with and without metabolic activation. Tester strain TA98NR (nitroductase deficient) is insensitive to the mutagenic activity associated with 1-nitropyrene. A summary of the linear portion of the dose response curve are given in Table 37 and are termed "specific activity" with units of:revertants per plate per microgram of SOF dosage. Table 37 also gives the "brake specific response," which was obtained by multiplying the specific activity by the SOF brake specific emission rate. The units for the brake specific response are then

$$\frac{\text{millions revertants/plate}}{\text{kW-hr.}}$$

Detailed results from the analysis of these SOF samples are given in the report from Southwest Foundation for Biomedical Research and is given as Appendix J.

Specific activity of SOF from operation on DF-2 was lowest on all five tester strains with metabolic activation. Although the levels of specific activity were greater for SOF from operation on DF-2 on all five tester strains without metabolic activation, the specific activities noted for DF-2 were generally lower than for the SOF from operation on the shale oil crudes. SOF from operation on DF-2 had the lowest total of measured PAH (Table 36). Generally, specific activities were lowest on tester strain TA98NR, followed by TA102, TA98, TA97A, and highest on TA100. The highest average of specific activities with and without metabolic activation occurred with SOF from operation on Geokinetics which also had the highest total of measured PAH (Table 36). On tester strain TA98NR, the specific activities for all SOF from the three crude shale oils were above the levels obtained for SOF from operation on DF-2. Combining the specific activities with SOF brake specific emissions yielded the brake specific response. The highest average of brake specific response was obtained for the Superior crude, then Paraho DOE, Geokinetics, and finally DF-2. Without metabolic activation, SOF from use of all three crudes resulted in a five-fold increase in the average brake specific response over that obtained from use of DF-2. With metabolic activation, approximately a ten-fold increase was noted for Geokinetics and an eighteen-fold increase for Paraho DOE and Superior.

TABLE 37. SUMMARY OF AMES RESPONSE TO TRANSIENT[a] SOF FROM THE IH DT-466B ON DF-2 AND CRUDE SHALE OILS

Fuel		Diesel[a]		Superior[a]		Geokinetics[a]		Paraho DOE[a]	
Fuel Code		EM-528-F		EM-584-F		EM-586-F		EM-585-F	
Total Particulate Rate, g/kW-hr		0.95		3.11		2.08		2.86	
Soluble Organic Fract., g/kW-hr		0.38		1.85		1.25		1.82	
Metabolic Activ. Status		No	Yes	No	Yes	No	Yes	No	Yes
Strain TA97A,	Test 1	1.263	0.349	0.962	1.675	1.575	1.385	1.625	2.175
Specific	Test 2	0.971	0.483	1.299	1.813	1.675	1.147	1.313	2.063
Activity[b]	Avg.	1.117	0.416	1.131	1.744	1.625	1.266	1.469	2.119
Avg. Brake Specific Response on TA97A[c]		0.42	0.16	2.09	3.23	2.03	1.58	2.67	3.86
Strain TA98,	Test 1	0.298	0.292	0.339	1.205	0.628	0.893	0.576	1.322
Specific	Test 2	0.355	0.260	0.630	1.510	0.528	1.054	0.519	1.293
Activity[b]	Avg.	0.327	0.276	0.485	1.358	0.578	0.974	0.548	1.308
Avg. Brake Specific Response on TA98[c]		0.12	0.11	0.90	2.51	0.72	1.22	1.00	2.38
Strain TA100,	Test 1	1.508	0.665	1.750	2.032	1.788	2.097	1.575	1.282
Specific	Test 2	1.611	0.566	1.523	2.375	2.963	1.162	1.678	1.425
Activity[b]	Avg.	1.560	0.616	1.637	2.204	2.376	1.630	1.627	1.354
Avg. Brake Specific Response on TA100[c]		0.59	0.23	3.03	4.08	2.97	2.04	2.96	2.46
Strain TA102,	Test 1	0.413	0.260	0.799	0.990	0.611	0.438	0.374	0.781
Specific	Test 2	0.688	0.388	0.554	0.720	0.655	0.527	0.458	0.733
Activity[b]	Avg.	0.551	0.324	0.677	0.855	0.633	0.483	0.416	0.757
Avg. Brake Specific Response on TA102[c]		0.21	0.12	1.25	1.58	0.79	0.60	0.76	1.38
Strain TA98NR,	Test 1	0.278	0.161	0.364	1.077	0.508	0.646	0.358	0.907
Specific	Test 2	0.267	0.142	0.344	0.851	0.588	0.566	0.377	1.080
Activity[b]	Avg.	0.273	0.152	0.354	0.964	0.548	0.606	0.368	0.994
Avg. Brake Specific Response on TA98NR[c]		0.10	0.06	0.66	1.78	0.69	0.76	0.67	1.81
Average of all 5 Strains, Brake Specific Response[c]		0.29	0.14	1.59	2.64	1.44	1.31	1.61	2.38

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[a] SOF from hot-start transient operation only.

[b] Specific Activity results from statistical analysis-given as "linear slope" revertants/plate per microgram of SOF dose. Each sample was tested in replicate.

[c] Brake Specific Response has units of: millions of revertants/plate per kilowatt hour.

902 1/6 [illegible]

VI. EVALUATION OF ENGINE WEAR AFTER OPERATING ON CRUDE SHALE OIL

This section summarizes the results of various inspections conducted on the engine after testing with crude shale oil.

A. Engine Teardown and Inspection

Several borescope inspections of the engine's cylinder liners and piston tops were conducted during the course of both preliminary test work and emissions test work. Overall, about 40 hours of operation were accumulated on the engine from the "as received" condition. Of this 40 hours, approximately 32 hours were accumulated with crude shale oils. From the initial borescope inspection, conducted after preliminary test work on DF-2, deterioration of the cylinder liners (especially liner No. 4) was apparent and continued to worsen with further engine operation on the various fuels. Since liner scuffing started with operation on DF-2, it is impossible to attribute the further deterioration of the cylinder liners to operation on the heated crude shale oils. In addition, it is impossible to estimate what portion of the deterioration was due to operating the engine on heated (200°F to 250°F) diesel fuel while preparing to switch to operation on heated shale oil.

Recall that after operating the engine on Geokinetics shale oil for emissions test purposes, borescope inspection revealed the formation of slight depressions at the apex of the piston crowns of all six cylinders. This condition appeared to have worsened after operation on the Paraho DOE shale oil. Although liner scuffing and piston damage were apparent, loss of maximum power in conjunction with lower maximum fuel flow indicated that perhaps the fuel injection pump had deteriorated by operation on the crude shale oils. To investigate the deterioration noted, the engine's head was removed for inspection of the valves, liners and pistons. The injection pump and injectors were removed and sent to a local commercial fuel injection service facility for examination and comparison with specified operating parameters.

An overall view of the head is shown in Figure 41, and a close-up of the combustion chambers of cylinders 5 and 6 given in Figure 42. Deposits were relatively light. Recall that the engine was operated on DF-2 for about 1 hour prior to subsequent removal of the head. Liner scuffing was quite apparent. Figure 43 shows liner scuffing on cylinder No. 4. The arrow indicates an apparent ring-to-liner weld or corrosion. A similar mark was noted on cylinder liner No. 2, indicated by the longer arrow in Figure 44. The shorter arrows in Figure 44 point to two areas where other liner damage was apparent. From the positions of these marks, found to some degree on each cylinder liner, relative to that of the crankshaft, it would appear that the damage occurred during storage of the engine or after shut-down for some extended period of time. From these observations, we attribute the development of liner scuffing to the interruption of cylinder liner-ring lubrication at these concentric liner disruptions, and not to the use of crude shale oil alone.

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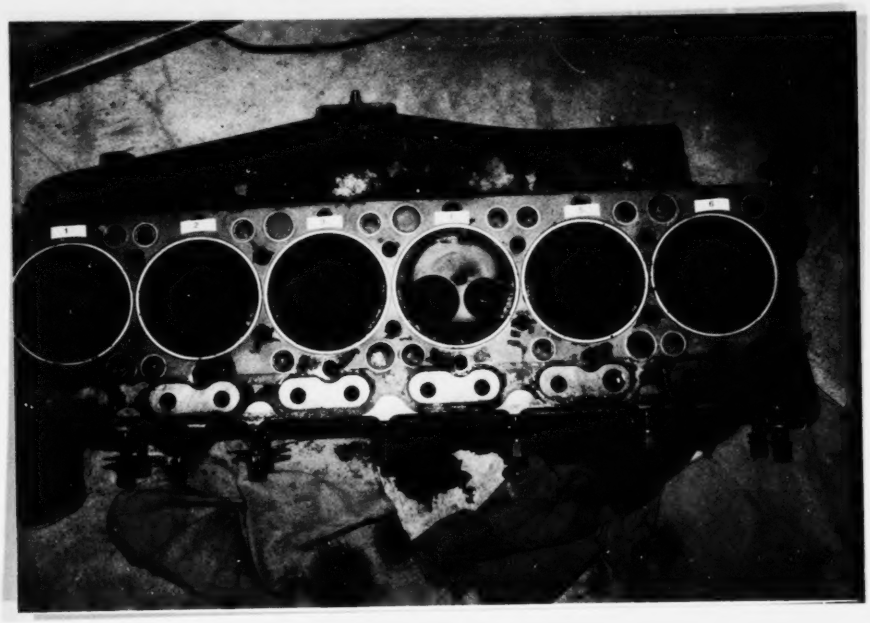

Figure 41. Overview of head from DT-466B after operation on DF-2 and three crude shale oils

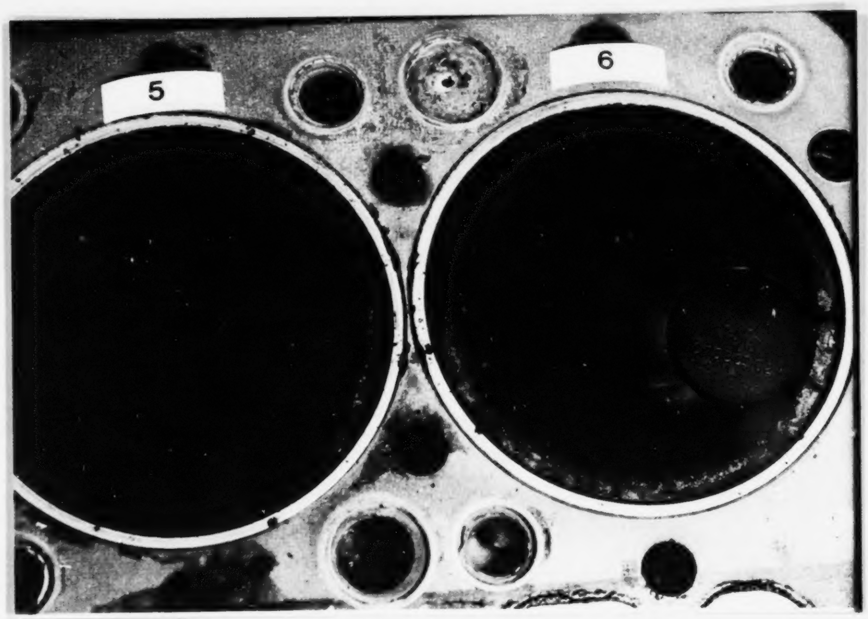

Figure 42. Close-up of head side of Cylinders No. 5 and 6

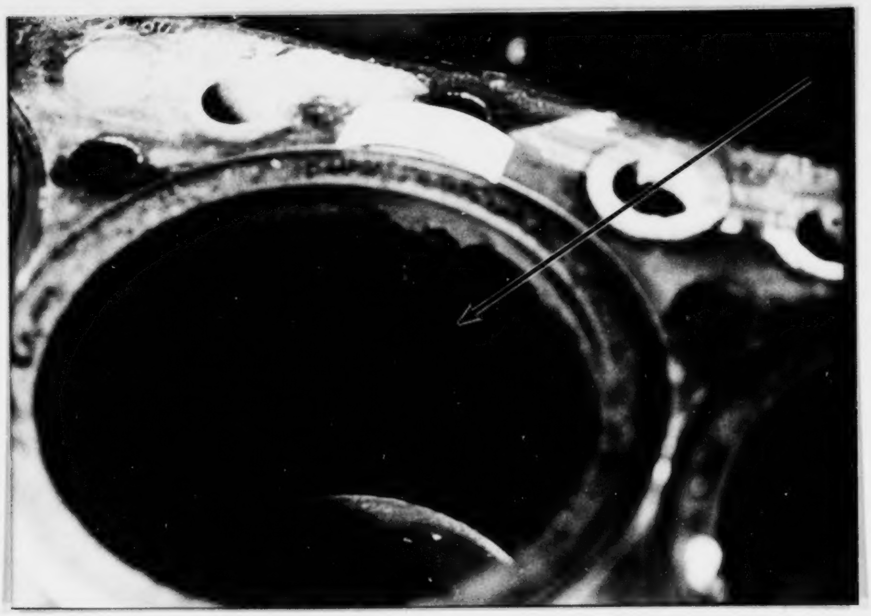

Figure 43. Cylinder liner No. 4

Figure 44. Cylinder liner No. 2

With the head removed, the tops of the pistons were exposed for examination. As mentioned earlier, depressions were formed in the tops of the piston crowns. The depressions were apparent on all six pistons, and are shown in Figures 45 through 48. In addition, Figures 45, 47, and 48 show another point of erosion (designated by the arrow) which occurred on all six pistons in the same relative position. This position is also in approximate alignment with one of the nozzle holes in the injector. On piston No. 6, shown in Figure 48, this erosion appeared to be stair-stepped in shape. From a telephone conversation with Mr. Bernie Sipes of International Harvester on May 25, 1984, depressions in the top center of the piston have occurred with use of very low-cetane fuels or when oil control by the top ring has deteriorated. The erosion noted on the perimeter of the piston crown has also occurred with low-cetane fuels and is thought to be a result of a distortion of the swirl pattern, which in turn, distorts the flame front from its intended positioning. In addition, the tunnel-shaped deposits which formed around the nozzle holes of the injector, shown in Figure 37, may have also contributed to deterioration of the piston tops.

Although cetane numbers of the crude shale oils were not determined in this program, it was expected that the cetane number might be similar to that of diesel fuel since the shale oil materials contained a wide range of higher boiling point materials. It is conjecture that the low boiling point materials present in the crude shale oils contributed to depressing the cetane number, causing problems with deterioration and subsequent piston crown damage. We and EPA would welcome any comments from those who have experienced this type of piston deterioration.

Based on the intended use of this engine, to conduct follow-on testing with minimally-processed shale oil fuels, it was decided to rebuild the engine with new International Harvester liners, pistons and rings. In addition, rod end bearings showed signs of normal wear, and were replaced during the rebuild. The head and valves were inspected and serviced by a local machine shop as necessary.

B. Fuel Injection Pump and Injector Teardown and Inspection

Upon receiving the engine for use in this program, the fuel injection pump was sent out for calibration. When refitted to the engine, the maximum power was in the range of 210 to 213 hp with about 87 lb/hr of DF-2. By the end of the program, the maximum power had dropped to about 187 hp with about 82 lb/hr of DF-2. In addition, the idle speed had dropped from the initial 750 rpm to near 630 rpm by the end of the program. The injection pump and injectors were removed and sent to a local fuel injection repair facility (M&D Distributors, San Antonio, Texas) for inspection and service.

Results of initial and final injection pump calibration checks, given in Table 38, indicated that injection pump performance had deteriorated. The injection pump was dismantled and an inspection for worn parts found that the primary cause for loss of maximum power fuel flow and the reduction of low idle speed was the deterioration of the friction clutch drive of the governor. This drive mechanism consists of two disc springs (one behind the other, with spacer in between) driving the spider assembly (governor weights, pins, and bushings) through the resulting contact area.

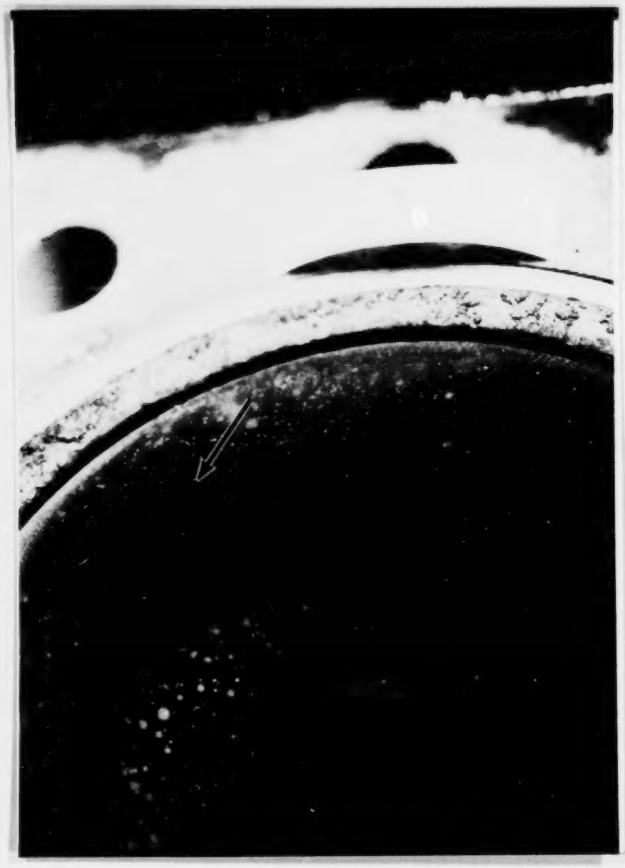

Figure 45. Top of Piston No. 1

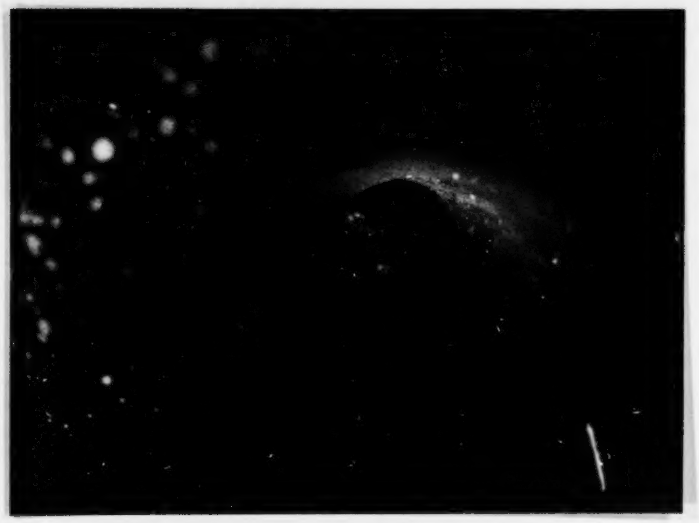

Figure 46. Close-up of No. 1 piston crown, center

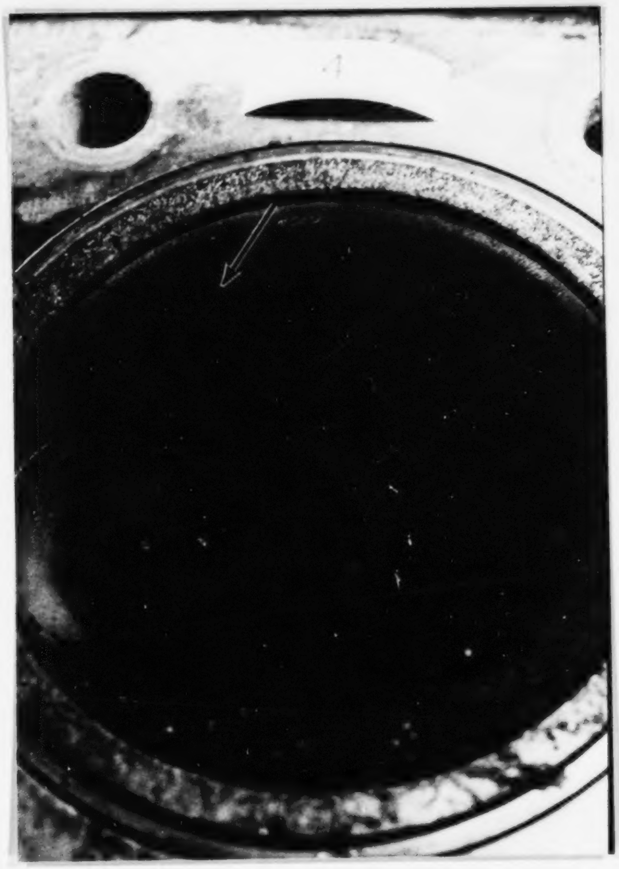

Figure 47. Top of Piston No. 4

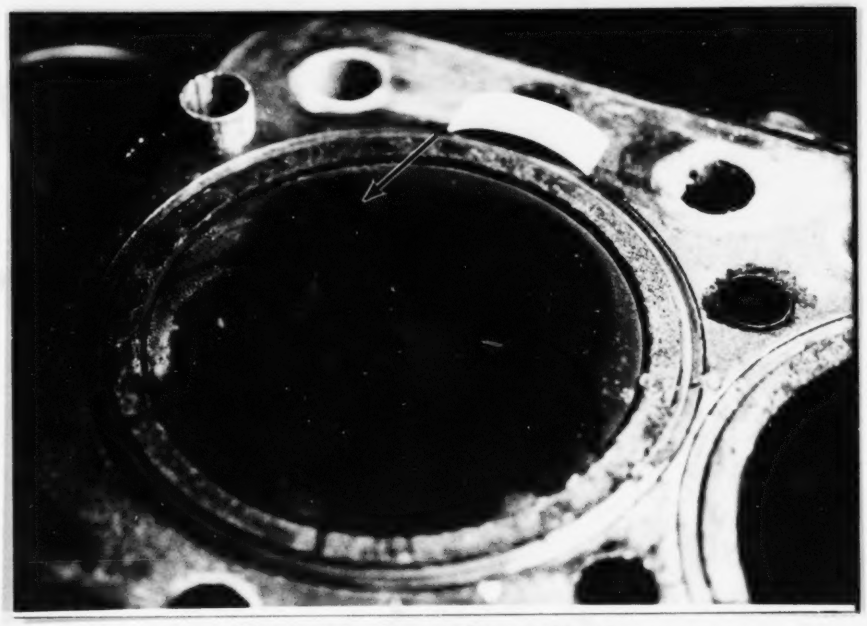

Figure 48. Top of Piston No. 6

TABLE 38. RESULTS OF DT-466B FUEL INJECTION PUMP INSPECTIONS

Test Condition			Injection Pump and Governor Test			
			Test Point Readings			
No.	Speed, rpm	Boost, psi	Specified	Initial	Final	Test Simulation
1	2600	15	47.5 cc	47.5	45.5	full load
2	2600	0	37-41 cc	39.0	37.5	full load
3	2100	15	48.0 cc	48.0	44.0	peak torque
4	2675	15	C.D., rpm	2680	2710	cam nose departure
5	3150	15	2 cc, max.	2.0	3.0	break in
6	1600	15	45.5 cc	45.5	39.5	droop speed
7	625	0	9.5 cc	12.0	5.5	low idle
8	150	0	10 cc, min.	15.0	10.5	cranking (200 strokes)

This oil-lubricated friction drive should transmit between 34 and 44 in lb torque, but when checked, torque transmission was limited to 10 in lb. This low torque transfer caused improper governor operation which in turn caused improper fuel flow during engine operation. Test points 4, 5, and 7 of Table 38 are affected most strongly by the friction drive. Figure 49 shows the two disc springs along with the spider to which the governor weights are attached. The arrows in Figure 49 indicate the friction drive surfaces. Wear of these surfaces are no greater than normal, but the spring rates of the two disc springs were below specifications. This type of damage is normally the result of very high engine oil temperatures. The temperature of the engine oil during testing did not exceed that of normal operation, but is is probable that the auxiliary heating of the injection pump in conjunction with the heated crude shale oil caused the deterioration in the spring rate of the friction clutch drive.

Results of test point 8 of the pump and governor test, Table 38, indicated some deterioration in the hydraulic head assembly. The fuel flow decreased from 15 to 10.5 cc with 200 strokes at 150 rpm cranking. The low limit at this flow check condition was 10 cc. Figure 50 shows the parts associated with the hydraulic head of the injection pump. No damage to the delivery valve assembly was noted (shown as item 1 in Figure 51). Figure 51 shows the plunger assembly along with the mating sleeve, item 2. These two parts mate with a minimal clearance sufficient for a sliding fit, and are not tolerant of any debris in the fuel. All fuel introduced to the engine is delivered through this fuel metering plunger and sleeve. On the plunger, the distributor slot is identified as 3, the fill port by 4, and the spill port by 5. Wear marks were noted next to both the fill port and spill port. The wear between these portions of the plunger and the sleeve are indeterminable, but the result of overall wear was indicated by the reduced cranking flow noted for test point 8 of Table 38. Due to undocumented use of this pump prior to its use in this program, it is impossible to determine what portions of these wear marks were due to operation on the crude shale oil. The plunger sleeve along with the other parts of the hydraulic head assembly, were replaced with new parts in preparation for operation on minimally-processed shale oils.

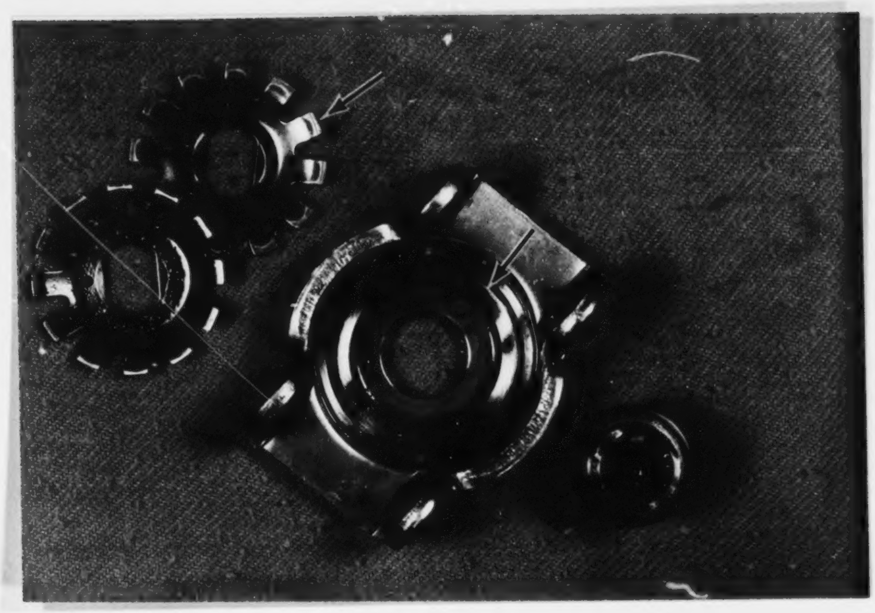

Figure 49. Friction drive of governor spider assembly

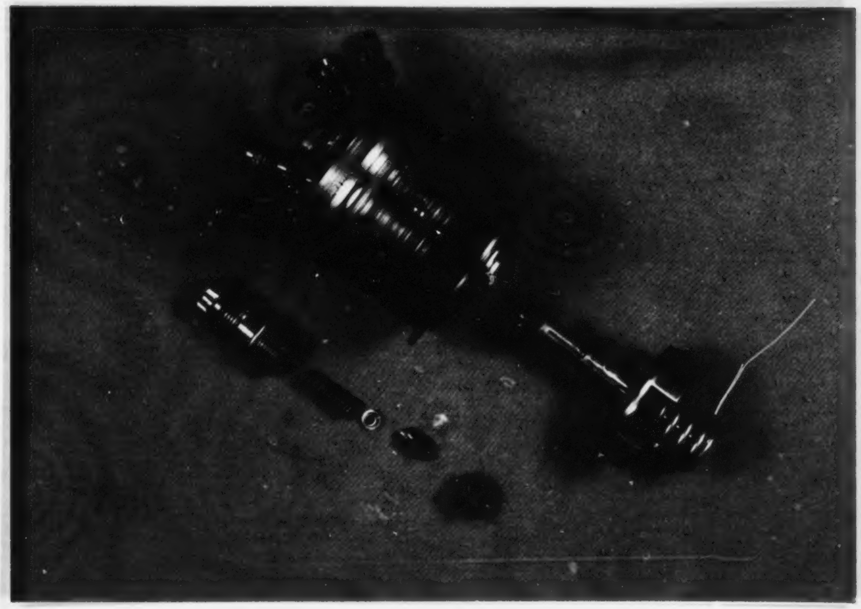

Figure 50. Hydraulic head of injection pump of DT-466B

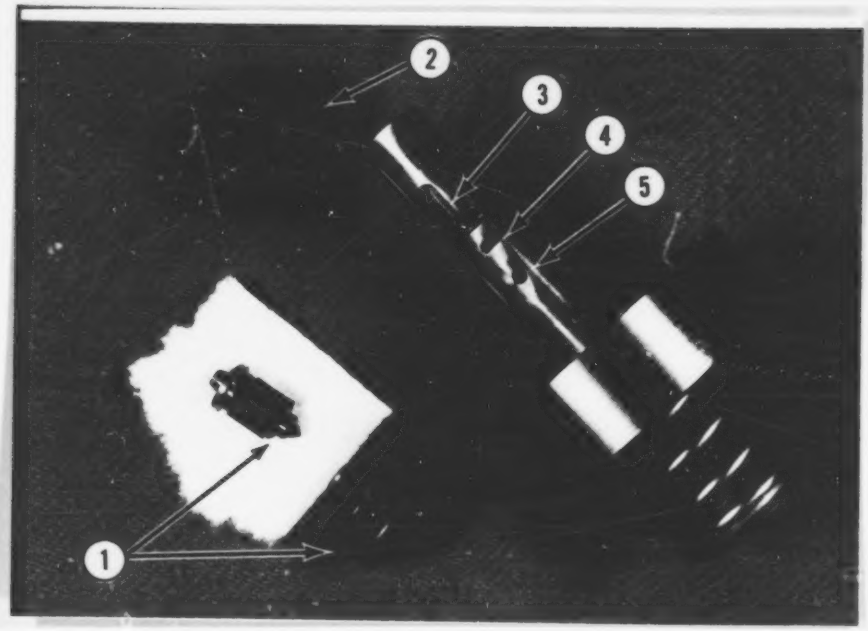

Figure 51. Close-up of fuel metering parts from the hydraulic head of the injection pump

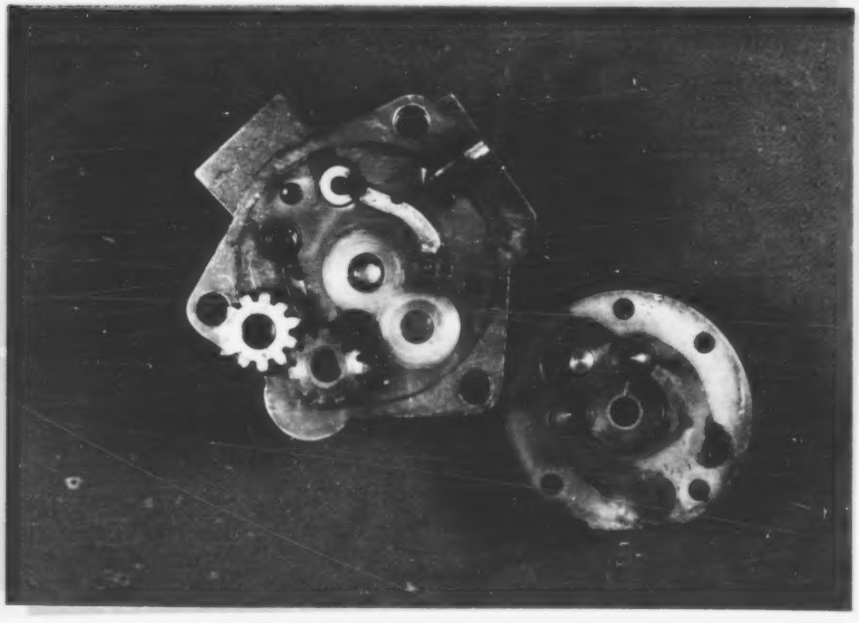

Figure 52. Fuel transfer pump of the fuel injection pump

All DF-2 and crude shale oils were pumped through the fuel transfer pump of the injection pump. Figure 52 shows the dismantled transfer pump. No unusual wear was noted from operation on the crude shale oils.

As mentioned earlier, the injectors were also inspected after completion of the crude shale oil program. Table 39 gives information as to the condition of all six injectors. New injectors should have a cracking pressure of between 3600 and 3750 psi, with a service limit of 2900 psi before replacement.

TABLE 39. RESULTS OF INJECTOR INSPECTION

Injector No.	Opening Press., psi	Atomization	Comments
1	3000	Poor	no chatter, dribble
2	3000	Poor	no chatter, dribble
3	3200	OK	one hole plugged
4	3200	OK	best
5	3300	OK	best
6	3250	OK	one hole partially plugged

Although all injector opening pressures were above the service limit, injectors 1 and 2 had the lowest opening pressure and poor atomization. Ironically, injector No. 4, which was suspected to have poor atomization (thus causing liner scuffing of No. 4 cylinder), was rated as one having the best atomization of the remaining injectors. All six injectors were reworked for replacement in the engine.

VII. EMISSION RESULTS FROM OPERATION IN MINIMALLY-PROCESSED SHALE OILS

This section gives emissions results obtained over both transient and steady-state testing of the International Harvester DT-466B heavy-duty diesel engine, operated on two minimally-processed shale oils. The section is divided into three parts. General test notes are given in the first part to describe engine operating characteristics and observations. Detailed analyses of exhaust emissions obtained over cold- and hot-start transient testing on the baseline and two minimally-processed shale oils are given in the second part for gaseous emissions, and then in the third part for particulate-related emissions.

A. General Test Notes

A few specification fuels have been refined from crude shale oils in the past, at considerable cost relative to refining conventional petroleum crude oil. Since the diesel engine is exceptionally "fuel tolerant," is was expected that minimally-processed shale oils might be suitable for direct introduction as fuel in heavy-duty diesel engine operation. The ability to consume minimally-processed shale oils would be expected to substantially reduce the cost of utilizing shale oil. Two 55-gallon drum quantities of each of two candidate minimally-processed shale oils were obtained from the DOE Synthetic Fuels Center for use in this program. The two materials were derived from crude shale oil holdings of Geokinetics, Inc., and were processed through their Caribou refinery. One was labeled as "Distillate Shale Crude," and was coded as EM-600-F. The other was labeled "High Nitrogen Hydrocracker Feed," and was coded EM-599-F. Both materials had good cetane numbers, and other properties which appeared to pose little problem with introducing them to the engine.

Since these two "fuels" were not expected to damage the engine beyond that which had occurred during operation on the crude shale oils, the engine was rebuilt. Rebuild of the International Harvester DT-466B included installation of new pistons, rings and liners. New rod end bearings were installed. The head was reconditioned with new valve guides, valves and springs as needed. In addition, the head was checked for cracks, and none were found. The fuel injection pump and all six injectors were reconditioned. A complete set of new injector lines was installed, and the fuel handling system was returned to the stock configuration. Fuel injection was timed to 16.5^{o}BTDC (which was the timing of engine "as-received").

The rebuilt engine was installed in transient test-capable Cell 1, and was operated over the manufacturers prescribed break-in procedure. In addition, 20 hours of maximum power operation were conducted to stabilize engine performance and emissions on DF-2 baseline fuel (EM-597-F). A new baseline was to be established on DF-2 since the engine was rebuilt. The rebuilt test engine was mapped as prescribed by the transient test procedure using DF-2. Over the map, the maximum torque was 477 ft-lb at 1900 rpm, and the maximum power was 208 hp at 2600 rpm. Idle speed was 692 rpm. The results of the torque map are given in Table F-1, Appendix F. The resulting transient cycle command had a total transient cycle work of 13.45 hp-hr (4.6 percent greater than obtained for the previous baseline on DF-2).

This transient cycle command was used for testing on baseline DF-2 and on both minimally-processed shale oils. The engine was operated over a practice transient test in order to make the necessary dynamometer control adjustments to meet statistical criteria for transient engine operation. Sample flow rates for several particulate and gaseous sample systems were established. Once again, the relatively large CVS (shown in Figure 32) was used for single dilution of the engine's exhaust.

Two complete transient test sequences (each consisting of a cold- and hot-start transient test) were performed on baseline DF-2 (Test 5, Run 1 and Run 2). Following completion of transient test work, a single 13-mode test (Test No. 5) was conducted. During that 13-mode test, a maximum power of 209.4 hp was observed at 2600 rpm with 84.5 lb/hr of DF-2. Smoke opacity was determined over 13 modes of steady-state operation and over the FTP for smoke. After completing the planned emissions characterization on DF-2 (EM-597-F), the engine's injectors were removed, and a borescope inspection was performed. Figure 53 shows the deposits on the tips of all six injectors from operation on DF-2, and they appeared to be normal. The borescope inspection (Report No. 8 Table I-1) indicated that cylinder liner wear was good ("clear"), with only a slight presence of bore polish on cylinder liners No. 5 and 6.

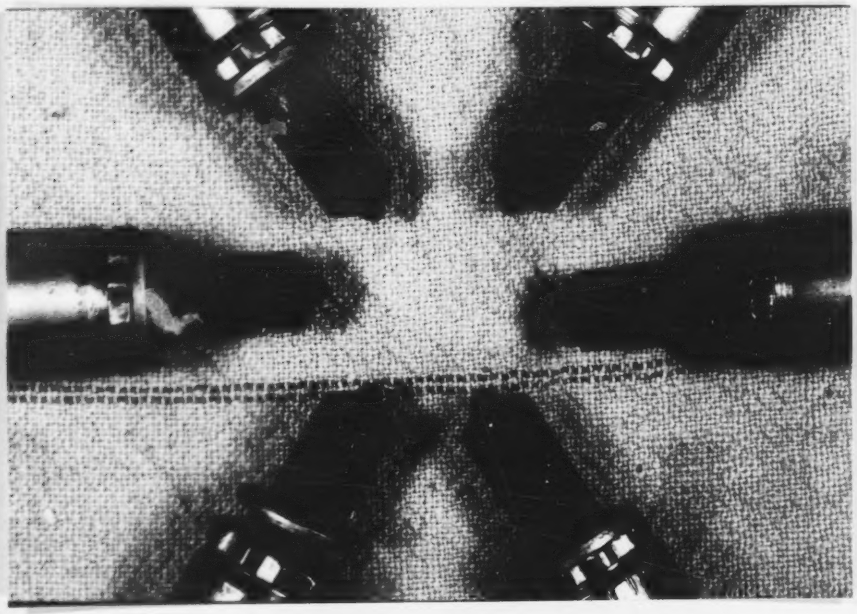

Figure 53. Injector Nozzle tips after operation on DF-2 (EM-597-F)

Of the two minimally-processed shale oils on hand, EM-599-F, or the High Nitrogen Hydrocracker Feed (HNHF) appeared to be most like diesel fuel in regard to physical properties. This hydrotreated shale oil material had a very high cetane number (58), had a H/C mole ratio of 1.99, and contained about 88 percent saturates (by FIA). Based on these properties, the fuel system was switched over without modification from DF-2 (EM-597-F) to the HNHF (EM-599-F). The engine was operated at maximum power on this fuel for about 30 minutes in order to purge the fuel system. The engine performed well on this fuel, but some reduction in full power was observed, which corresponded to a reduction in fuel mass flow. The percent change (-5.5 percent) agreed well with the lower density of EM-599-F, at 0.8022 grams/ml, versus the density of the baseline DF-2, EM-597-F, at 0.8488 grams/ml. A practice transient cycle was performed using the same transient cycle command developed from operation on DF-2, No problems with meeting the statistical criteria were noted.

As on the baseline fuel, two complete transient test sequences were performed on the HNHF (Test No. 6 Run 1 and Run 2). No problems were encountered during cold-start-up for transient testing. A single 13-mode test was conducted on HNHF and the maximum power during that run was 198.0 hp (-5.4 percent from baseline) at 2600 rpm with 79.3 lb/hr of fuel. After completing measurements of steady-state and FTP smoke opacities, the injectors were removed for borescope inspection of the cylinder liners. Figure 54 shows the deposits on the injectors after 5 hours of operation on EM-599-F.

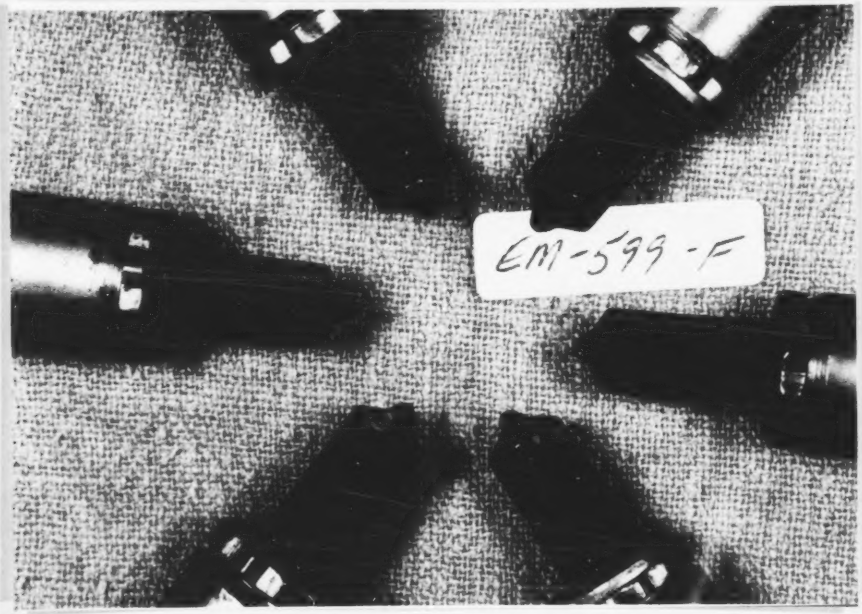

Figure 54. Injector Nozzle tips after operation on HNHF (EM-599-F)

The deposits were not noticeably different from those noted on DF-2. Similarly, borescope inspection of the cylinder liners (Report No. 9) showed no noticeable difference from operation on DF-2 other than that the tops of the pistons had a reddish tint, along with some gray-colored deposits.

The fuel was changed to EM-600-F, shale oil Distillate, and the engine operated at maximum power for approximately 20 minutes to insure that the fuel system was purged of the previous fuel tested. Observed power was similar to that obtained on DF-2 (EM-597-F). The Distillate shale oil fuel had a very strong odor, and was black in color, similar to that of the crude shale oil run in the previous project phase. The viscosity of this material was low enough so that no preheating was needed. The fuel temperature measured at the inlet to the injection pump was maintained near 100° ±10°F. Following 20 minutes of purge operation, the engine was operated over a transient test cycle, and no problems with engine performance or meeting the statistical criteria of the transient test were noted. Engine start-up for the cold-start transient test went well, and no problems with engine operation or fueling were encountered. We were concerned that this material (EM-600-F) might cause some problems with vapor lock in the fuel filter since it contained some light ends.

Two transient test sequences (Test No. 7, Run 1 and Run 2) were completed on Distillate. During the 13-mode test (Test No. 7), the engine developed a maximum power of 205.4 hp at 2600 rpm with 85.2 lb/hr of shale oil Distillate. No problems were encountered over 13-mode steady-state or FTP operation for smoke opacity measurements. After about 6 hours of operation on EM-600-F, a borescope inspection (Report No. 10) was conducted, and it showed no noticeable deterioration. The tops of the pistons had a gray tint with no carbon build-up. Deposits on the injector tips are shown in Figure 55, and were heavier than obtained on DF-2 or HNHF, but not nearly as heavy as noted on the crude shale oils. It is possible that greater deposits would have accumulated with extended operation on Distillate.

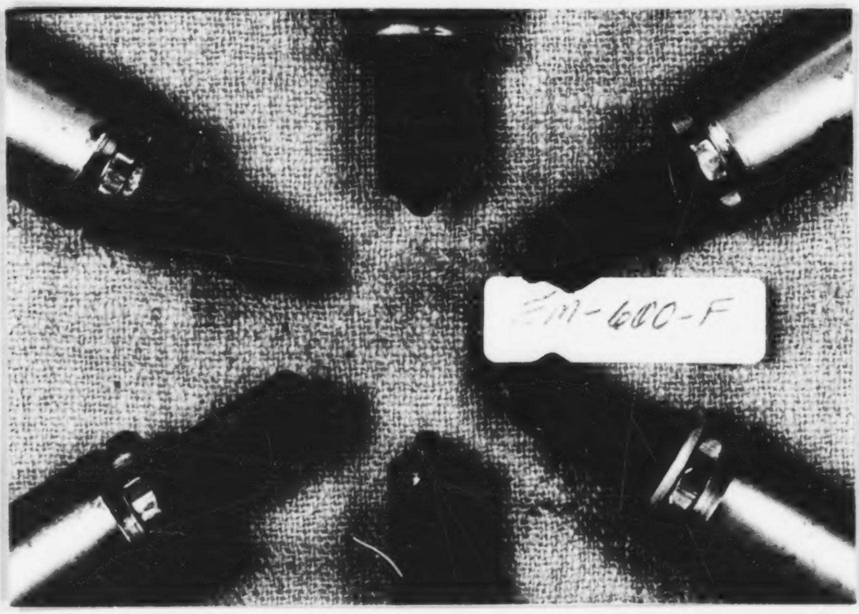

Figure 55. Injector nozzle tips after operation on Distillate (EM-600-F)

After completing the test work, the engine's fuel system was purged with DF-2. Following about one hour of maximum power operation on DF-2, the fuel filters of both the engine and Flo-tron were changed, and the engine was operated for another 2 hours at rated power conditions. Since there was no change in performance following operation on the two minimally-processed shale oils, and because no damage was noted during the borescope inspections, no teardown or further inspection of the engine was carried out.

B. Gaseous Emissions

The term "gaseous emissions," as used in this section, refers not only to HC, CO, and NO_x emissions, but also includes emissions of selected individual hydrocarbons, ammonia, cyanide, aldehydes, and phenols. Results of these analyses, along with results of odor intensity measurements, are given in this section.

1. HC, CO, and NO_x

These regulated pollutants were measured over the 1979 13-mode FTP as well as the 1984 Transient FTP. Detailed emissions characterization was conducted on the International Harvester DT-466B heavy-duty diesel engine over the 1984 Transient FTP, whereas only HC, CO, and NO_x emissions were determined over the 1979 13-mode FTP. Results from transient testing of the DT-466B on the baseline DF-2 and two minimally-processed shale oil fuels are given in Table 40. Detailed results from individual cold-start and hot-start runs are given in Appendices F, G, and H for testing on DF-2, (EM-597-F) HNHF (EM-599-F), and Distillate (EM-600-F), respectively. Results from the individual runs are tabulated in Table 40 along with their averages for cold- and hot-start operation. Average transient composite results, given in Table 40, were computed by weighting the average cold- and hot-start values per the 1984 Transient Procedure.

Transient composite emissions of HC, CO, and NO_x from operation on DF-2 and the two minimally-processed shale oil fuels were all below the 1984-1985 regulated emission levels. On DF-2, emission levels were somewhat greater over the cold-start transient than over the hot-start transient. This trend was also noted on both minimally-processed shale oils. On the HNHF (EM-599-F), all regulated emissions were lower than with the baseline DF-2. Average composite HC emissions on HNHF were 22 percent lower than obtained on DF-2 (EM-597-F). Average composite CO emissions were also somewhat lower (15 percent) on HNHF (EM-599-F). Average composite NO_x emissions were approximately 16 percent lower when tested on this shale oil material (containing rather low nitrogen, despite the implication of the name). Although fuel-bound nitrogen does affect the NO_x emissions to some degree, the apparent reduction in NO_x emissions may be the result of the relatively high cetane number providing a smoother pressure rise with lower peak temperature.(24)

TABLE 40. REGULATED EMISSIONS SUMMARY FROM TRANSIENT FTP OPERATION OF THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Test Fuel	Test No.	Run No.	Cycle Type	Transient Emissions, g/kW-hr(g/hp-hr)				Cycle BSFC^{a,b} kg/kW-hr (lb/hp-hr)	Cycle Work kW-hr (hp-hr)
				HC	CO	NO_x	Part.		
DF-2 EM-597-F	5	1	Cold	1.29 (0.96)	3.38 (2.52)	12.16 (9.07)	0.86 (0.64)	0.275 (0.452)	9.66 (12.96)
	5	2	Cold	1.35 (1.01)	3.51 (2.62)	11.65 (8.69)	0.91 (0.68)	0.270 (0.444)	9.71 (13.02)
		Average Cold		1.32 (0.98)	3.45 (2.57)	11.91 (8.88)	0.88 (0.66)	0.272 (0.448)	9.69 (12.99)
	5	1	Hot	1.13 (0.84)	2.70 (2.01)	11.55 (8.61)	0.83 (0.62)	0.255 (0.420)	9.69 (12.99)
	5	2	Hot	1.14 (0.85)	2.68 (2.00)	11.24 (8.50)	0.75 (0.59)	0.254 (0.417)	9.75 (13.07)
		Average Hot		1.13 (0.84)	2.69 (2.00)	11.39 (8.50)	0.79 (0.59)	0.254 (0.418)	9.72 (13.03)
	Average Transient Composite			1.16 (0.86)	2.80 (2.08)	11.46 (8.55)	0.80 (0.60)	0.257 (0.422)	9.72 (13.02)

TABLE 40 (CONT'D). REGULATED EMISSIONS SUMMARY FROM TRANSIENT FTP OPERATION OF THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Test Fuel	Test No.	Run No.	Cycle Type	Transient Emissions, g/kW-hr(g/hp-hr)				Cycle BSFC^{a,b} kg/kW-hr (lb/hp-hr)	Cycle Work kW-hr (hp-hr)
				HC	CO	NO_x	Part.		
HNHF EM-599-F	6	1	Cold	0.98 (0.73)	2.83 (2.11)	10.46 (7.80)	0.64 (0.48)	0.267 (0.439)	9.63 (12.92)
	6	2	Cold	0.89 (0.66)	2.86 (2.13)	10.47 (7.81)	0.63 (0.47)	0.265 (0.436)	9.64 (12.93)
		Average Cold		0.93 (0.70)	2.84 (2.12)	10.47 (7.80)	0.64 (0.48)	0.266 (0.438)	9.64 (12.92)
	6	1	Hot	0.91 (0.68)	2.19 (1.63)	9.51 (7.09)	0.55 (0.41)	0.246 (0.405)	9.66 (12.95)
	6	2	Hot	0.89 (0.66)	2.40 (1.79)	9.49 (7.08)	0.58 (0.43)	0.246 (0.404)	9.65 (12.94)
		Average Hot		0.90 (0.67)	2.29 (1.71)	9.50 (7.08)	0.56 (0.42)	0.246 (0.404)	9.65 (12.94)
	Average Transient Composite			0.90 (0.67)	2.37 (1.77)	9.64 (7.18)	0.57 (0.43)	0.249 (0.409)	9.65 (12.94)

TABLE 40 (CONT'D). REGULATED EMISSIONS SUMMARY FROM TRANSIENT FTP OPERATION OF THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Test Fuel	Test No.	Run No.	Cycle Type	Transient Emissions, g/kW-hr(g/hp-hr)				Cycle BSFC[a,b] kg/kW-hr (lb/hp-hr)	Cycle Work kW-hr (hp-hr)
				HC	CO	NO_x	Part.		
Distillate EM-600-F	7	1	Cold	1.54 (1.15)	4.55 (3.39)	12.23 (.912)	1.17 (0.87)	0.274 (0.451)	9.66 (12.96)
	7	1	Cold	1.42 (1.06)	4.25 (3.17)	11.84 (8.83)	1.33 (0.99)	0.263 (0.433)	9.72 (13.03)
	Average Cold			1.48 (1.10)	4.40 (3.28)	12.04 (8.98)	1.25 (0.93)	0.269 (0.442)	9.69 (13.00)
	7	1	Hot	1.19 (0.89)	3.10 (2.31)	12.07 (9.00)	0.91 (0.68)	0.261 (0.429)	9.67 (12.97)
	7	2	Hot	1.49 (1.11)	2.99 (2.23)	11.45 (.854)	0.85 (0.63)	0.249 (0.409)	9.75 (13.08)
	Average Hot			1.34 (1.00)	3.04 (2.27)	11.76 (8.77)	0.88 (0.66)	0.255 (0.418)	9.71 (13.02)
	Average Transient Composite			1.36 (1.01)	3.23 (2.41)	11.80 (8.80)	0.93 (0.70)	0.257 (0.421)	9.71 (13.02)

---

[a] based on carbon balance

[b] fuel carbon fraction: EM-597-F, 0.861; EM-599-F, 0.855; EM-600-F, 0.852

Operation of the DT-466B on Distillate (EM-600-F) caused all the regulated emissions to increase from the levels obtained on baseline (DF-2). The average transient composite level of HC emissions increased by 17 percent, and the average transient composite CO level increased by 16 percent. A slight increase (3 percent) in the average transient composite level of NO_x emissions was also noted on Distillate shale oil (EM-600-F). The cetane number of this material was 41, only slightly lower than the cetane number of the DF-2 at 46.

There was no change in BSFC over transient FTP testing with DF-2 and Distillate. However, on HNHF (with cetane number of 58), BSFC was 3 percent below the level obtained on DF-2 (EM-597-F). There was little change in cycle work over all the transient test work with these fuels; and no problems were encountered in meeting the statistical criteria for transient testing, even though the engine was not remapped on each fuel. Transient composite total particulate, which will be discussed in a later section, decreased by 28 percent on the HNHF, but increased by 17 percent on the distillate as compared to DF-2.

A 13-mode test was conducted on each fuel after completing the transient testing on that fuel. Results from the single 13-mode test on each fuel are summarized in Table 41. Detailed results of each test are given in the Appendices along with additional engine parameters, in Tables F-1 and F-2 for DF-2, Tables G-1 and G-2 for HNHF, and Tables H-1 and H-2 for Distillate.

TABLE 41. GASEOUS EMISSIONS SUMMARY FROM 13-MODE OPERATION OF THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

		13-Mode			
		Emissions, g/kW-hr, (g/hp-hr)			BSFC kg/kW-hr (lb/hp-hr)
Test Fuel	Test No.	HC	CO	NO_x	
DF-2 EM-597-F	05-01	0.94 (0.70)	2.24 (1.67)	11.63 (8.67)	0.249 (0.410)
HNHF EM-599-F	06-01	0.83 (0.62)	1.82 (1.36)	10.04 (7.48)	0.248 (0.407)
Distillate EM-600-F	07-01	0.94 (0.70)	2.43 (1.81)	12.23 (9.12)	0.262 (0.430)

As with previous testing on crude shale oils, the 13-mode FTP results from operation on the baseline DF-2 fuel and the two minimally-processed shale oils were about the same as those obtained over transient testing. On DF-2, the 13-mode HC and CO emissions levels were about 19 percent below those obtained for the transient FTP. The 13-mode composite NO_x emission level was 1.4 percent above that obtained on the transient FTP on DF-2. The BSFC over the 13-mode test was about 2 percent lower than that obtained during transient testing.

On HNHF (EM-599-F), emission trends noted over transient operation were also noted for 13-mode operation, namely that HC, CO, and NO_x were lower along with a slight improvement in BSFC. Comparing 13-mode composite results on HNHF to those obtained on DF-2, HC emissions were down by 11 percent, CO emissions were down by almost 19 percent, and NO_x emissions were 8 percent lower. No improvement in BSFC was noted over the 13-mode test with the HNHF as a fuel.

Over the 13-mode test on Distillate (EM-600-F), no change in HC emissions was noted from the level obtained on DF-2, even though an increase had been noted over transient FTP testing with this fuel. In addition, an 8 percent increase in composite CO emissions over 13-mode operation on DF-2 was noted when Distillate was used. This change in CO emissions was greater over the transient FTP on this fuel. Although little change in transient FTP NO_x emissions was noted with Distillate shale oil (EM-600-F), NO_x emissions on the 13-mode FTP increased by about 5 percent over the level obtained with DF-2. No change in BSFC was noted during transient FTP testing with Distillate, but 13-mode BSFC increased by about 5 percent over that obtained on DF-2.

2. Selected Individual Hydrocarbons

Certain individual hydrocarbons (IHC) were determined by processing CVS-diluted exhaust samples using chromatographic techniques to separate methane, ethylene, ethane, acetylene, propylene, propane, benzene, and toluene. These determinations were conducted for each of the replicate transient tests conducted with each of the three test fuels. Results from the individual transient tests are given in Appendix Tables F-6 and F-7 for DF-2, Tables G-5 and G-6 for HNHF, and Tables H-5 and H-6 for Distillate. Average results for both cold- and hot-start transient tests given in these Appendix Tables have been carried forward and are summarized in Table 42.

Aside from methane, which appeared to be more variable in its concentration, repeatability of replicate tests were good. As with the crude shale oil test work, no propane or toluene were found over transient operation on either of the two minimally-processed fuels or on the baseline DF-2. Ethylene was the most prevalent hydrocarbon species for all the fuels tested, followed by propylene, methane, and acetylene. Small concentrations of benzene and ethane were also noted.

The IHC total emission levels were obtained by simply adding the emission levels of the individual species for a given fuel. IHC total emissions were always greater for the cold-start than over the hot-start transient test. The total IHC level was somewhat lower on both minimally-processed shale oils than on baseline DF-2. This might be expected for the HNHF, since total HC's by HFID (given in Table 40) were somewhat lower; but it was not expected for the Distillate, which indicated greater total HC emissions by HFID. Ethylene accounted for about 53 to 70 percent of the IHC total for the three fuels, and propylene accounted for about 11 to 30 percent. Acetylene (hot-start), which accounted for about 2 to 5 percent of the total IHC, was lowest for operation on the HNHF, higher on DF-2, and highest on Distillate.

TABLE 42. INDIVIDUAL HYDROCARBONS FROM TRANSIENT OPERATION OF THE IH DT-466B ENGINE ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Test Fuel	Transient Cycle	Units	Individual Hydrocarbons								IHC
			Methane	Ethylene	Ethane	Acetylene	Propane	Propylene	Benzene	Toluene	"Total"
DF-2 EM-597-F	Cold Start	mg/test	220	910	4.0	65	0	530	0	0	1700
		mg/kW-hr	23	94	0.41	6.7	0	55	0	0	180
		mg/kg fuel	83	350	1.5	25	0	200	0	0	660
	Hot Start	mg/test	290	710	8.8	46	0	180	39	0	1300
		mg/kW-hr	30	73	0.88	4.7	0	19	4.0	0	130
		mg/kg fuel	120	290	3.5	19	0	74	1.6	0	520
HNHF EM-599-F	Cold Start	mg/test	370	830	7.5	43	0	240	0	0	1500
		mg/kW-hr	38	86	0.80	4.5	0	25	0	0	150
		mg/kg fuel	150	330	2.9	17	0	93	0	0	590
	Hot Start	mg/test	0	710	0	20	0	230	70	0	1000
		mg/kW-hr	0	73	0	2.0	0	24	7.5	0	110
		mg/kg fuel	0	300	0	8.0	0	94	30	0	430
Distillate EM-600-F	Cold Start	mg/test	190	870	0	56	0	380	60	0	1600
		mg/kW-hr	20	88	0	5.8	0	39	6.0	0	160
		mg/kg fuel	73	340	0	21	0	150	23	0	610
	Hot Start	mg/test	50	840	0	61	0	270	39	0	1300
		mg/kW-hr	5.0	85	0	6.3	0	28	4.0	0	130
		mg/kg fuel	21	340	0	25	0	110	16	0	510

3. Aldehyde

Aldehydes were determined by the liquid chromatograph DNPH procedure. Dilute samples were taken over replicate cold- and hot-start transient tests. Results from the individual runs are given in the Appendices, Tables F-8 and F-9 for DF-2, Tables G-7 and G-8 for HNHF, and Tables H-7 and H-8 for Distillate. Results from these individual runs were averaged and are given in Table 43 for cold- and hot-start transient testing. Total aldehyde emission levels were obtained by adding the emissions of various species. Of the species, formaldehyde was most prevalent; followed by acetaldehyde; then propionaldehyde, isobutyraldehyde and MEK as a group; followed by lesser levels of the remaining aldehydes. In most cases, aldehyde emission levels over the cold-start cycle were above the levels obtained over the hot-start cycle. Considering total aldehydes, the highest levels were obtained with operation on baseline DF-2, then Distillate, and least on HNHF.

4. Phenols

Phenols were determined from dilute exhaust samples taken over single runs of cold- and hot-start transient operation. The detection of individual phenols in dilute exhaust is quite variable, particularly when working with relatively low concentrations. From analysis of all the samples taken, only those from both cold-start and hot-start operation on Distillate indicated the presence of a phenol compound, 2,3,5-trimethylphenol. Computed emissions of this phenol compound are given in Table 44. No other phenols were noted above the detection limits, which are about 11 mg/test, 1.1 mg/kW-hr, or 4.4 mg/kg fuel.

TABLE 44. EMISSIONS OF 2,3,5,-TRIMETHYLPHENOL FROM TRANSIENT OPERATION OF THE DT-466B ON DISTILLATE SHALE OIL (EM-600-F)

	2,3,5-Trimethylphenol Emissions	
Units	Cold-Start	Hot-Start
mg/test	13	32
mg/kW-hr	1.3	3.2
mg/kg fuel	5.0	12

5. Cyanide

Total cyanide, including hydrogen cyanide (HCN) and cyanogen (C_2N_2), was determined from dilute exhaust samples obtained individually over cold- and hot-start transient operation. Table 45 summarizes the results obtained from these individual samples. It should be noted that the cyanide emissions determined over baseline operation on DF-2 are about 10 times the level determined over hot-start operation on DF-2 during the original baseline, established prior to running the crude shale oil. At this point, we are not sure what caused this difference in baseline levels and have reviewed analysis and calculations concerning all of the cyanide emission data. Comparing the results obtained from the three fuels tested during this program phase, it appears that no significant change in cyanide emissions occurred.

TABLE 43. SUMMARY OF ALDEHYDES FROM TRANSIENT OPERATION OF THE IH DT-466B ENGINE ON DF-2 AND MINIMALLY-PROCESSED SHALE OIL

Test Fuel	Transient Cycle	Units	Form-aldehyde	Acet-aldehyde	Acrolein	Propion-aldehyde	Acetone	Croton-aldehyde	Isobutyr-aldehyde & MEK	Benz-aldehyde	Hexan-aldehyde	Total Aldehydes
DF-2 EM-597-F	Cold Start	mg/test	1200	370	240	190	47	54	240	52	58	2400
		mg/kW-hr	120	38	25	20	4.8	5.5	24	5.4	6.0	250
		mg/kg fuel	440	140	92	72	18	20	89	20	22	910
	Hot Start	mg/test	980	250	130	170	47	69	190	73	69	2000
		mg/kW-hr	100	26	13	17	4.8	7.1	19	7.5	7.1	200
		mg/kg fuel	400	100	53	67	19	28	75	30	28	800
HNHF EM-599-F	Cold Start	mg/test	700	240	52	240	0	45	120	30	48	1500
		mg/kW-hr	73	25	5.4	25	0	4.6	13	3.1	5.0	150
		mg/kg fuel	280	93	20	95	0	17	48	12	19	580
	Hot Start	mg/test	540	78	78	180	0	7.7	62	40	68	1000
		mg/kW-hr	56	8.2	8.0	18	0	0.8	6.4	4.2	7.1	110
		mg/kg fuel	230	33	33	75	0	3.2	27	17	29	440
Distillate EM-600-F	Cold Start	mg/test	1100	330	63	310	0	72	180	62	78	2200
		mg/kW-hr	120	34	65	32	0	7.5	18	6.4	8.0	230
		mg/kg fuel	440	120	25	120	0	28	67	24	30	850
	Hot Start	mg/test	760	260	120	220	120	75	99	38	28	1700
		mg/kW-hr	79	27	13	23	12	7.8	10	3.9	2.9	180
		mg/kg fuel	310	100	99	90	50	30	39	15	11	750

TABLE 45. SUMMARY OF CYANIDE EMISSIONS FROM TRANSIENT FTP OPERATION OF THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Test Fuel	Cycle	Total Cyanide Emissions mg/test	mg/kW-hr	mg/kg fuel
DF-2	Cold	95	9.9	36
EM-597-F	Hot	110	11	44
	Composite	110	11	43
HNHF	Cold	89	9.2	34
EM-599-F	Hot	34	3.5	14
	Composite	42	4.3	17
Distillate	Cold	120	12	47
EM-600-F	Hot	120	12	48
	Composite	120	12	48

6. Ammonia

Ammonia was determined from dilute exhaust samples taken individually over cold- and hot-start transient operation. A summary of the results is given in Table 46. Operation on both of the minimally-processed shale oil fuels yielded lower emissions of ammonia than on DF-2. The fact that no ammonia above the minimum detectable level was noted for operation on Distillate is puzzling, and tends to indicate a lack of dependence on fuel-bound nitrogen for the formation of ammonia. It is possible that low levels of ammonia were not noted due to interference caused by the presence of other compounds in the exhaust or as a result of other exhaust products absorbing the ammonia to produce some form of salt such as ammonium sulfate.

TABLE 46. SUMMARY OF AMMONIA EMISSIONS FROM TRANSIENT OPERATION OF THE DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Test Fuel	Transient Cycle	Ammonia Emissions mg/test	mg/kW-hr	mg/kg fuel
DF-2	Cold Start	1100	110	410
EM-597-F	Hot Start	900	93	360
	Composite	930	96	370
HNHF	Cold Start	530	55	200
EM-599-F	Hot Start	160	17	68
	Composite	210	22	88
Distillate	Cold Start	<380[a]	<40[a]	<150[a]
	Hot Start	<360[a]	<37[a]	<150[a]
	Composite	<360[a]	<37[a]	<150[a]

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[a] based on minimum detectable levels

7. Odor - TIA

Total intensity of aroma (TIA) was determined from DOAS analysis of dilute exhaust samples taken individually over cold- and hot-start transient operation. Results from individual analyses are given in Table 47 along with computed transient composite values. There was little difference in TIA on the basis of liquid column aromatic (LCA) for the three fuels tested. TIA by LCA was generally lower for the cold-start than for the hot-start. On the basis of liquid column oxygenate (LCO), TIA was slightly greater for all three fuels tested as compared to TIA by LCA, and the level of TIA was slightly greater with the two minimally-processed shale oils than that obtained on DF-2.

TABLE 47. SUMMARY OF TIA BY DOAS[a] FROM TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Test Fuel	Transient Cycle	LCA, µg/ℓ	TIA[b]	LCO, µg/ℓ	TIA[c]
DF-2	Cold Start	10.83	1.12	2.60	1.41
EM-597-F	Hot Start	22.61	1.35	4.25	1.63
	Composite	20.93	1.32	4.01	1.60
HNHF	Cold Start	20.27	1.31	6.72	1.83
EM-599-F	Hot Start	22.34	1.34	7.19	1.86
	Composite	22.04	1.34	7.12	1.86
Distillate	Cold Start	29.38	1.43	13.40	2.13
EM-600-F	Hot Start	33.57	1.47	8.36	1.92
	Composite	32.97	1.46	9.08	1.95

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[a] These measurements were based on DOAS standard corresponding for use of No. 2 diesel fuel. Samples were taken from exhaust diluted approximately 12:1 for the overall transient cycle.

[b] TIA based on liquid column aromatics (LCA) by:
$\text{TIA} = 0.4 + 0.7 \log_{10} (\text{LCA})$

[c] TIA based on liquid column oxygenates (LCO) by:
$\text{TIA} = 1 + \log_{10} (\text{LCO})$,(TIA by LCO preferred)

C. Particulate Emissions

In order to determine particulate emission rates and to characterize the total particulate, samples were collected on several filter media for a variety of analyses which included total mass, elemental analysis, and organic extractables. Particulate samples were always taken from the dilute exhaust using a CVS. Smoke was measured as an indication of visible particulate emission levels on each of the three fuels.

1. Smoke

Smoke and particulate emissions are related, smoke levels being a measure of the visible portion of particulate matter. Smoke opacity was determined using an end-of-stack PHS smokemeter. Table 48 summarizes the smoke opacity data obtained over both steady-state modal operation and smoke FTP operation. Detailed results from smoke FTP chart readings are given in the Appendices, Table F-10 for DF-2, Table G-9 for HNHF, and Table H-9 for Distillate.

TABLE 48. SUMMARY OF SMOKE OPACITY FROM THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Federal Transient Smoke Cycle Opacity, %

Test Fuel	Accel.	Lug	Peak
DF-2 EM-597-F	10.8	9.8	16.5
HNHF EM-599-F	8.7	3.7	12.7
Distillate EM-600-F	9.8	4.3	16.2

13-Mode			Smoke Opacity, %, by Fuel		
Mode	RPM	Power, %	DF-2 EM-597-F	HNHF EM-599-F	Distillate EM-600-F
1	690	-	0.1	0.1	0.3
2	1800	2	0.1	0.4	0.7
3	1800	25	0.1	0.7	1.0
4	1800	50	1.5	1.8	2.2
5	1800	75	2.4	2.7	2.8
6	1800	100	6.3	4.6	5.0
7	690	-	0.1	0.3	1.0
8	2600	100	5.5	5.0	4.7
9	2600	75	1.0	2.1	2.2
10	2600	50	0.7	1.6	2.3
11	2600	25	0.6	2.4	2.2
12	2600	2	0.5	1.5	2.0
13	690	-	0.1	0.1	1.0

On DF-2, the FTP smoke opacities were somewhat lower than statutory limits. On HNHF, the FTP smoke opacities were somewhat lower than those obtained on the baseline fuel, particularly over the lug portion. One reason for lower smoke during "full rack" operation while on HNHF was this fuel's lower specific gravity, compared to the baseline DF-2. FTP smoke opacities while on Distillate were similar to the values obtained on DF-2 with the exception of the lug portion, which was about half the level noted on DF-2. No dense white smoke peaks at the beginning of the test cycle accelerations were noted as they had been for testing on the crude shale oils. Modal steady-state smoke emissions on both minimally-processed fuels were slightly lower than obtained on DF-2 during the high load conditions. However, somewhat higher levels of smoke opacity than on DF-2 were noted for the rated speed and moderate load conditions on both minimally-processed shale oils, especially on Distillate.

2. Total Particulate

Total particulate was determined over replicate cold- and hot-start transient operation of the DT-466B. Results from the individual tests are given in Table 49, along with the average levels of total particulate and computed transient composites. More details associated with sample flows and filter efficiencies are given in the computer printouts for the individual test results, presented in the Appendices corresponding to the various fuels. On DF-2, the transient composite of total particulate emissions from cold- and hot-start testing was 0.80 g/kW-hr, or 0.60 g/hp-hr. Total particulate emissions were slightly greater from the cold-start transient than from the hot-start transient test for all three fuels tested.

On the HNHF, the transient composite of total particulate was about 29 percent lower than obtained on the baseline DF-2. In fact, even the cold-start total particulate emissions with HNHF were 20 percent below the composite particulate emission rate obtained on DF-2. On Distillate, the transient composite of total particulate increased by 16 percent over that obtained on the baseline DF-2. The cold-start emission of total particulate was noticeably higher than for the hot-start on the Distillate shale oil.

3. Soluble Organics

The soluble organic fraction (SOF) of the total particulate was determined by extraction of relatively large particulate samples. The results of these analyses are also given in Table 49. Following rebuild of the engine, the hot-start SOF was 36 percent, down from nearly 41 percent during the previous baseline on DF-2. For the most recent baseline on DF-2, the SOF accounted for 36.2 percent of the transient composite of total particulate, with SOF emissions of 0.28 g SOF/kW-hr. On the HNHF, the percentage of SOF changed very little; however, when considering the lower total particulate emission on this fuel, the emission of SOF was 0.22 g SOF/kW-hr (a 21 percent reduction in SOF emissions from the baseline level).

In contrast to the use of the hydrotreated shale oil (HNHF), transient operation on the Distillate shale oil yielded a higher percentage of SOF in the total particulate. On Distillate, the transient composite percent SOF increased to 50 percent. When this level of percent solubles is combined

TABLE 49. TOTAL PARTICULATE AND SOLUBLE ORGANIC FRACTION FROM TRANSIENT FTP OPERATION OF THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

				Total Particulate		Percent	Soluble Organic Fraction	
Test Fuel	Test No.	Run No.	Cycle Type	g/kW-hr	g/kg fuel	SOF	g /kW-hr	g /kg fuel
DF-2 EM-597-F	1	1	Cold	0.86	3.13	34.1	0.29	1.07
	1	2	Cold	0.91	3.37	42.9	0.39	1.45
		Avg		0.88	3.25	38.5	0.34	1.26
	1	1	Hot	0.83	3.25	30.2	0.25	0.98
	1	2	Hot	0.75	2.95	41.4	0.31	1.22
		Avg		0.79	3.10	35.8	0.28	1.10
	Average Transient Composite			0.80	3.12	36.2	0.29	1.12
HNHF EM-599-F	2	1	Cold	0.64	2.40	38.7	0.25	0.93
	2	2	Cold	0.63	2.38	38.6	0.24	0.92
		Avg		0.64	2.39	38.6	0.25	0.92
	2	1	Hot	0.55	2.24	38.5	0.21	0.86
	2	2	Hot	0.58	2.36	36.5	0.21	0.86
		Avg		0.56	2.30	37.5	0.21	0.86
	Average Transient Composite			0.57	2.31	37.7	0.22	0.89
Distillate EM-600-F	3	1	Cold	1.17	4.27	57.0	0.67	2.43
	3	2	Cold	1.33	5.06	44.3	0.59	2.24
		Avg		1.25	4.67	50.6	0.63	2.34
	3	1	Hot	0.91	3.49	52.3	0.48	1.82
	3	2	Hot	0.85	3.41	48.7	0.41	1.66
		Avg		0.88	3.45	50.5	0.44	1.74
	Average Transient Composite			0.93	3.62	50.5	0.47	1.83

with the higher total particulate emissions on Distillate, the emissions of soluble organic material are 0.47 g SOF/kW-hr (an increase in SOF emissions of 62 percent over that obtained on DF-2).

4. Sulfate

Sulfate was determined from samples of total particulate collected on Fluoropore filter media during replicate runs of cold- and hot-start transient operation. Results of sulfate analysis by the BCA method are summarized in Table 50. Since the sulfate originates from the sulfur contained in the fuel, sulfate emissions were computed in terms of mg/kg fuel and percent of fuel sulfur converted to ($SO_4^=$).

On DF-2 (EM-597-F), containing 0.35 weight percent sulfur, transient composite sulfate emissions were 53 mg/kW-hr, representing about 1.9 percent conversion of fuel sulfur to sulfate. Compared to these levels obtained on DF-2, sulfate emissions were much lower on the HNHF and somewhat higher on the Distillate.

On the HNHF, containing less than 0.01 weight percent sulfur, the transient composite sulfate emissions were determined to be about 5 mg/kW-hr, which would represent about a 6.3 percent conversion of fuel sulfur to sulfate. This level of conversion appears to be abnormally high, and in consideration of the low fuel sulfur content, it is possible that the values for sulfate emissions with the HNHF are overstated. On Distillate, containing 0.53 weight percent sulfur, transient composite sulfate emissions were 80 mg/kW-hr, representing about 2.0 percent fuel sulfur conversion to sulfate.

A trend noted from comparison of sulfate emissions is that the cold-start level is often higher than the hot-start level. One possible reason for this occurrence may be that generally emission of ammonia is often greater during the cold-start (see Table 46). Higher concentrations of ammonia would promote conversion of SO_2 gases to $SO_4^=$ precipitate or aerosol, which is collected as particulate and identified as sulfate. The fact that no ammonia above the detectable limit was noted on Distillate may have been caused by the ammoniation of SO_2 and SO_3 to ammonium sulfate aerosol, thereby consuming what little ammonia may have been produced. Other unknown interferences associated with the use of Distillate may have caused the low readings of ammonia.

5. Elemental Composition

Elemental analysis of the total particulate required two particulate samples. Carbon, hydrogen and nitrogen content of the total particulate were determined by Galbraith Laboratories, using oxidation techniques on particulate samples collected by glass fiber filter media. Sulfur and metal content were determined by EPA-RTP from particulate samples collected on Teflon membrane (Fluoropore) filter media, using x-ray fluorescence techniques.

A summary of elemental analysis is given in Table 51. There was little difference in carbon content from cold-start and hot-start transient operation on any of the three fuels. Sulfur content was least on HNHF, but iron

TABLE 50. SULFATE EMISSIONS FROM TRANSIENT FTP OPERATION OF THE IH DT-466B ENGINE ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Test Fuel	Transient Cycle	Run	Sulfate Emissions			% of Fuel S in $SO_4^=$
			mg/test	mg/kW-hr	mg/kg fuel	
DF-2	Cold	1	570	59	210	2.00
EM-597-F	Start	2	570	58	220	2.09
		Avg	570	59	215	2.05
	Hot	1	550	57	220	2.09
	Start	2	450	46	180	1.71
		Avg	500	52	200	1.90
	Average Transient Composite		510	53	200	1.92
HNHF	Cold	1	86	8.9	33	11.0
EM-599-F	Start	2	58	6.0	23	7.67
		Avg	72	7.5	28	9.34
	Hot	1	66	6.8	28	9.33
	Start	2	16	1.7	6.8	2.27
		Avg	41	4.3	17.4	5.80
	Average Transient Composite		45	4.8	19	6.31
Distillate	Cold	1	950	98	360	2.31
EM-600-F	Start	2	880	91	340	2.18
		Avg	915	95	350	2.25
	Hot	1	750	78	300	1.92
	Start	2	760	78	310	1.99
		Avg	755	78	305	1.96
	Average Transient Composite		780	80	320	2.00

TABLE 51. SUMMARY OF ELEMENTAL ANALYSIS OF TOTAL PARTICULATE FROM TRANSIENT OPERATION OF THE IH DT-466B ON DF-2 AND AND MINIMALLY-PROCESSED SHALE OILS

Individual Elements % wt.	DF-2, EM-597-F		HNHF, EM-599-F		Distillate, EM-600-F		Detection[d] Limit
	Cold	Hot	Cold	Hot	Cold	Hot	
C	62.9	64.2	81.6	80.7	63.8	68.7	a
H	--	5.5	6.4	6.3	6.3	6.8	a
N	0.6	0.7	0.3	0.3	1.7	1.6	a
S	3.25	3.49	0.353	0.258	3.42	3.94	0.017
Al	b	b	b	b	b	b	0.013
As	b	b	b	b	c	c	0.107
Ba	b	b	b	b	a	a	0.010
Br	b	b	b	b	b	b	0.202
Ca	0.098	0.107	0.655	0.153	0.094	c	0.026
Cd	b	b	b	c	0.036	0.033	0.005
Cl	b	b	c	c	b	b	0.007
Co	b	b	c	b	a	a	0.031
Cu	c	c	c	c	a	a	0.077
Cr	c	0.224	0.220	0.258	c	c	0.068
Fe	0.506	0.536	1.09	0.712	0.573	0.594	0.105
Hg	b	b	b	b	b	b	0.365
K	b	b	c	b	b	b	0.011
Mg	0.045	0.045	0.057	0.037	0.044	0.028	0.005
Mn	c	c	b	b	c	c	0.040
Mo	b	b	b	b	b	b	0.673
Na	c	c	b	b	c	c	0.087
Ni	c	c	c	c	c	c	0.044
P	0.109	0.097	0.098	0.085	0.101	0.072	0.006
Pb	b	b	b	b	b	b	0.585
Pt	b	b	b	b	a	a	0.203
Sb	c	c	b	c	a	a	0.006
Se	c	b	b	b	a	a	0.098
Si	b	b	c	b	b	b	0.029
Sn	c	b	b	b	a	a	0.031
Sr	b	b	b	b	b	b	0.263
Ti	b	b	0.047	c	c	c	0.009
V	b	b	b	b	b	b	0.020
Zn	c	c	c	c	0.547	0.525	0.054

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[a] No data

[b] Concentration below the detection limit

[c] Element was detected but was below the level of quantitation (3 x detection limit)

[d] Detection limit is dependent on particulate loading, three values are based on a loading of 0.6 mg (which was the range of loading for samples submitted for x-ray)

was highest on HNHF. Arsenic was below the level of quantitation on Distillate and was not detected on DF-2 on HNHF.

6. Boiling Point Distribution

A high-temperature GC-simulated boiling point distribution with internal standard (C_9-C_{11}) was conducted on the SOF from the total particulate collected over individual cold-start and hot-start transient tests on each of the three fuels. Chromatograms from analysis of SOF are given in Figure 56. The peak data from the internal standard, which has a retention time between 10 and 15 minutes, were omitted for the sake of simplicity. The vertical scale units of "mV" and "slice units" are for data manipulation by computer only, and can not be translated into meaningful units (Figure 56). Results were also plotted on a distillation chart in Figure 57. Boiling point temperature of several HC's with various carbon numbers have been designated by "NC-XX" on Figure 57 for comparative purposes. Additional discussion will be added when results are received.

7. Elemental Composition of SOF

The carbon, hydrogen, and nitrogen content of the SOF from cold- and hot-start transient operation on DF-2 and two minimally-processed shale oils are given in Table 52. Generally, the carbon content was about 85 percent for all three fuels over both cold- and hot-start tests. It appears that there might be a trend to higher carbon content with the two minimally-processed shale oils. Similarly, there was little difference in the hydrogen content of the SOF from use of the three fuels. The nitrogen content of the SOF appeared to follow the nitrogen content of the fuel. That is, for the HNHF fuel, with a nitrogen content of 0.05 percent, the hot-start SOF contained about 0.23 percent nitrogen. For the baseline DF-2 fuel, containing 0.08 percent, the SOF contained about the same as with the HNHF. Hot-start SOF from operation on Distillate, containing 1.23 percent fuel-bound nitrogen, contained about 0.84 percent nitrogen. Computed H/C mole ratios of the SOF are also given in Table 52, and although they do not correspond exactly with the H/C ratio of the fuel used, it is interesting that they follow the same rank order (namely, that the SOF from operation on HNHF has the highest computed H/C mole ratio).

TABLE 52. SUMMARY OF ELEMENTAL ANALYSIS OF SOF FROM TRANSIENT FTP OPERATION OF THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Test Fuel	Transient Cycle	Individual Elements, % by Weight			H/C Ratio
		C	H	N	
DF-2	Cold	85.08	13.14	0.27	1.84
EM-597-F	Hot	85.24	13.36	0.24	1.87
HNHF	Cold	85.28	13.67	0.20	1.91
EM-599-F	Hot	85.28	13.53	0.23	1.89
Distillate	Cold	85.65	13.27	0.80	1.84
EM-600-F	Hot	85.80	13.51	0.84	1.88

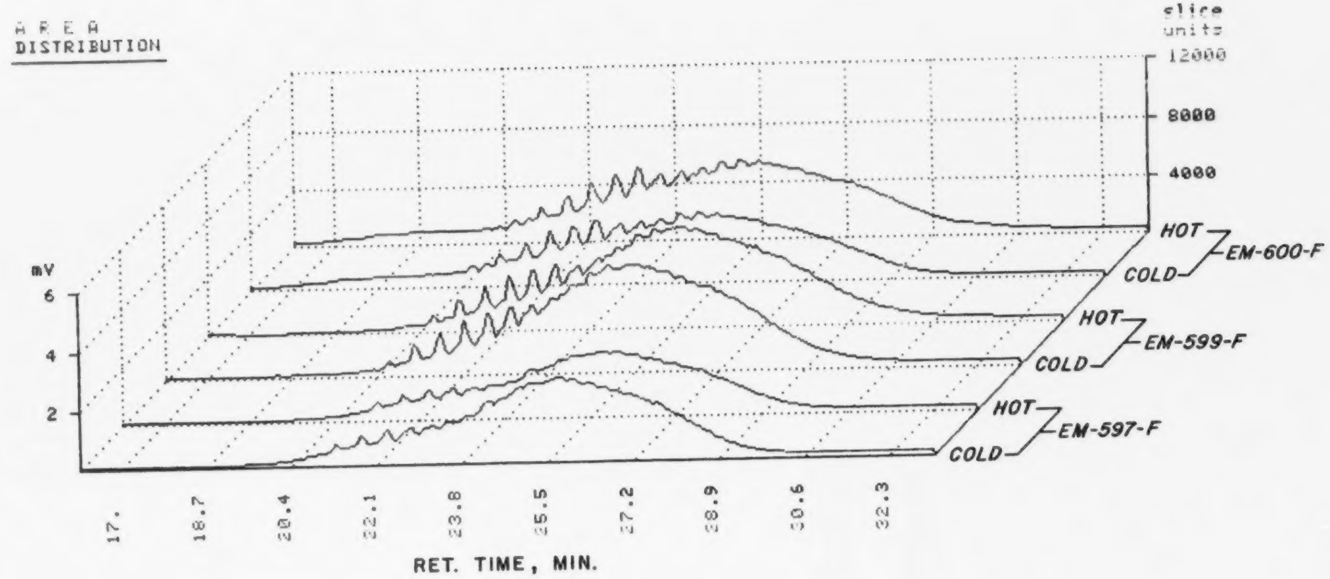

Figure 56. Area distribution of boiling point data obtained from SOF over Transient FTP operation of the IH DT-466B on DF-2 and two minimally-processed shale oils

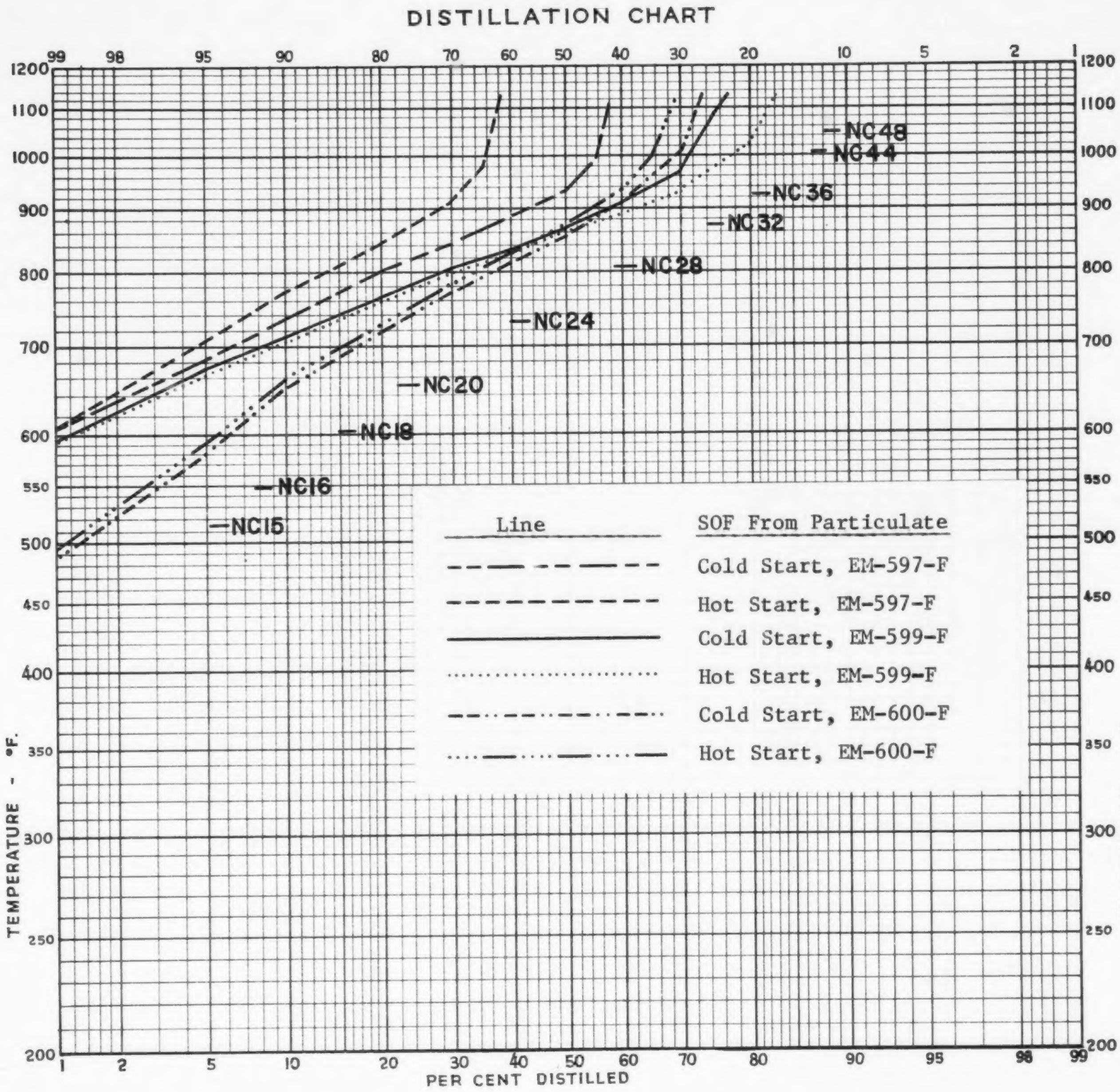

Figure 57. Boiling point distribution of SOF from Transient FTP operation of the IH DT-466B on DF-2 and two minimally-processed shale oils

8. Selected PAH Content of SOF

Samples of SOF derived from cold- and hot-start transient operation on DF-2 and minimally-processed shale oils were analyzed for various polynuclear aromatic hydrocarbons (PAH). Results from these analyses are given in Table 53. Of the six PAH's measured over this program for all three fuels, pyrene was most prevalent followed by emissions of chrysene, benz(a)anthracene, benzo(e)pyrene, benzo(a)pyrene and finally 1-nitropyrene. Compared to levels obtained on the baseline DF-2, operation on Distillate yielded the greatest overall emission of PAH. Pyrene accounted for almost 50 percent of the total measured PAH emission on Distillate, about 65 percent on HNHF and almost 38 percent on DF-2. Emissions of 1-nitropyrene were lower than for the baseline fuel on both minimally-processed fuels. Emissions of all but pyrene were lower on HNHF than on DF-2. In contrast, emissions of all but 1-nitropyrene were greatest on Distillate than on either HNHF or DF-2.

9. Bioassay of SOF

Samples of SOF obtained from cold- and hot-start transient tests were weighted 1/7 cold- and 6/7 hot-start. These composite transient extracts were submitted to Southwest Foundation for Biomedical Research for Ames bioassay. These samples were tested over five strains: TA97A, TA98, TA100, TA102, and TA98NR. A summary of the slopes of the dose response curves are given in Table 54. These slopes are based on the linear portion of the dose response curve and are labeled in the table as "specific activity." Table 54 also gives the "brake specific response" based on the average of specific activities found on replicate tests and the brake specific emission rate of SOF. Detailed results from these bioassays are given as Appendix J.

The specific activity of SOF from operation on DF-2, following engine rebuild, was higher for all five strains used, with or without metabolic activation, compared to the levels obtained for SOF from operation on HNHF or Distillate. Even though, total measured PAH (Table 53) for these two minimally-processed shale oils were greater than for the DF-2. Specific activities were generally lowest for TA98NR followed by TA102, TA98, TA97A, and highest on TA100. Relatively high specific activities were noted on strain TA97A without metabolic activation with SOF from operation on DF-2. This strain (TA97A) is sensitive to acridine type compounds. The resulting brake specific response for both HNHF and Distillate were lower than for the DF-2.

TABLE 53. SUMMARY OF 1-NITROPYRENE AND PAH OF SOF FROM TRANSIENT FTP OPERATION OF THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

PAH	Units	DF-2, EM-597-F Cold	DF-2, EM-597-F Hot	HNHF, EM-599-F Cold	HNHF, EM-599-F Hot	Distillate, EM-600-F Cold	Distillate, EM-600-F Hot
1-Nitropyrene	µg/g SOF	11	7.6	1.3	1.3	3.1	1.7
	µg/kW-hr	3.6	2.1	0.3	0.3	2.0	0.8
	µg/kg fuel	13	8.4	1.2	1.1	7.2	3.0
Pyrene	µg/g SOF	68	80	150	160	210	180
	µg/kW-hr	23	22	38	33	130	77
	µg/kg fuel	86	88	140	140	480	300
Chrysene	µg/g SOF	61	61	32	49	89	92
	µg/kW-hr	21	17	8.0	10	56	40
	µg/kg fuel	77	67	30	42	210	160
Benz(a)anthracene	µg/g SOF	21	18	16	18	57	56
	µg/kW-hr	7.1	5.0	4.0	3.8	36	25
	µg/kg fuel	26	20	15	15	130	97
Benzo(e)pyrene	µg/g SOF	16	14	12	29[a]	26	21
	µg/kW-hr	5.4	3.9	3.0	6.1	16	9.2
	µg/kg fuel	20	15	12	14	61	37
Benzo(a)pyrene	µg/g SOF	9.2	8.7	8.4	6.2	25	20
	µg/kW-hr	3.1	2.4	2.1	1.3	16	8.8
	µg/kg fuel	12	9.5	8.0	3.0	11	35
Total of Measured PAH	µg/g SOF	190	190	220	260	410	370
	µg/kW-hr	63	53	55	55	260	160
	µg/kg fuel	230	210	210	130	960	650

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[a] Chromatogram is different from others, value should be used with caution

TABLE 54. SUMMARY OF AMES RESPONSE TO TRANSIENT[a] SOF FROM THE IH DT-466B ON DF-2 AND MINIMALLY-PROCESSED SHALE OILS

Fuel		Diesel[a]		HNHF[a]		Distillate[a]	
Fuel Code		EM-597-F		EM-599-F		EM-600-F	
Total Particulate Rate, g/kW-hr		0.80		0.57		0.93	
Soluble Organic Fract., g/kW-hr		0.29		0.22		0.47	
Metabolic Activ. Status		No	Yes	No	Yes	No	Yes
Strain TA97A, Specific Activity[b]	Test 1	3.025	0.790	0.664	0.316	0.981	0.632
	Test 2	2.363	0.641	0.615	0.606	0.780	0.338
	Avg.	2.694	0.716	0.640	0.461	0.881	0.485
Avg. Brake Specific Response on TA97A[c]		0.78	0.21	0.14	0.10	0.41	0.23
Strain TA98, Specific Activity[b]	Test 1	0.963	0.784	0.321	0.264	0.348	0.399
	Test 2	0.992	0.720	0.235	0.399	0.539	0.623
	Avg.	0.978	0.752	0.278	0.332	0.444	0.511
Avg. Brake Specific Response on TA98[c]		0.28	0.22	0.06	0.07	0.21	0.24
Strain TA100, Specific Activity[b]	Test 1	2.225	1.041	0.728	0.808	1.093	0.596
	Test 2	0.761	2.663	0.677	0.691	1.017	0.709
	Avg.	1.493	1.852	0.703	0.750	1.055	0.653
Avg. Brake Specific Response on TA100[c]		0.43	0.54	0.16	0.17	0.50	0.31
Strain TA102, Specific Activity[b]	Test 1	0.725	0.470	0.500	1.013	0.225	0.187
	Test 2	0.259	0.700	0.250	0.390	0.107	0.369
	Avg.	0.492	0.585	0.375	0.702	0.166	0.278
Avg. Brake Specific Response on TA102[c]		0.14	0.17	0.08	0.15	0.08	0.13
Strain TA98NR, Specific Activity[b]	Test 1	0.626	0.387	0.254	0.180	0.190	0.231
	Test 2	0.551	0.313	0.181	0.131	0.188	0.296
	Avg.	0.589	0.350	0.218	0.156	0.189	0.264
Avg. Brake Specific Response on TA98NR[c]		0.17	0.10	0.05	0.03	0.09	0.12
Average of all 5 Strains, Brake Specific Response[c]		0.36	0.25	0.10	0.10	0.26	0.21

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[a] SOF weighted composite 1/7 cold-start + 6/7 hot-start.

[b] Specific Activity results from statistical analysis-given as "linear slope" revertants/plate per microgram of SOF dose. Each sample was tested in replicate.

[c] Brake Specific Response has units of: millions of revertants/plate per kilowatt hour.

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APPENDIX A

RESULTS FROM OPERATION ON EM-528-F, DF-2

TABLE A-1

13-MODE FEDERAL DIESEL EMISSION CYCLE 1979

ENGINE: IH DT466B　　　DF-2 CONTROL FUEL　　　BAROMETER 29.32
TEST-01-01　FUEL: EM-528-F　　　PROJECT: 03-7338-004　　　DATE: 02/09/84

MODE	POWER PCT	ENGINE SPEED COND / RPM	TORQUE OBS LB-FT	POWER OBS BHP	FUEL FLOW LB/MIN	AIR FLOW LB/MIN	INTAKE HUMID GR/LB	NOX CORR FACT	MEASURED HC PPM	MEASURED CO PPM	MEASURED CO2 PCT	MEASURED NOX PPM	CALCULATED GRAMS / HOUR HC	CALCULATED GRAMS / HOUR CO	CALCULATED GRAMS / HOUR NOX	MODE
1		IDLE / 700.	0.	.0	.043	5.74	78.	.993	315.	277.	1.39	270.	26.	46.	72.	1
2	2	INTER / 1800.	9.	3.0	.145	15.16	80.	1.012	335.	253.	2.05	215.	64.	95.	135.	2
3	25	INTER / 1800.	112.	38.4	.302	15.52	80.	1.014	322.	235.	4.19	485.	65.	92.	315.	3
4	50	INTER / 1800.	222.	76.2	.495	17.16	80.	1.010	265.	148.	6.28	845.	60.	64.	602.	4
5	75	INTER / 1800.	334.	114.6	.707	19.43	82.	1.013	247.	235.	7.99	1230.	64.	114.	986.	5
6	100	INTER / 1800.	445.	152.4	.945	22.09	82.	1.012	167.	691.	9.42	1380.	49.	379.	1251.	6
7		IDLE / 699.	0.	.0	.037	5.70	80.	.991	332.	249.	1.35	265.	24.	36.	62.	7
8	100	RATED / 2600.	431.	213.2	1.455	37.27	78.	1.004	105.	840.	8.38	1215.	53.	796.	1887.	8
9	75	RATED / 2600.	322.	159.5	1.075	32.03	78.	.998	158.	286.	7.24	1065.	68.	233.	1413.	9
10	50	RATED / 2600.	215.	106.6	.790	27.94	81.	.998	178.	131.	6.04	765.	67.	94.	895.	10
11	25	RATED / 2600.	109.	53.7	.515	24.38	81.	.994	252.	184.	4.46	460.	82.	116.	471.	11
12	2	RATED / 2600.	9.	4.3	.280	22.15	81.	.992	353.	235.	2.62	210.	103.	136.	196.	12
13		IDLE / 699.	0.	.0	.040	5.62	77.	.976	320.	263.	1.35	255.	25.	41.	64.	13

MODE	CALCULATED GRAMS/LB-FUEL HC	CALCULATED GRAMS/LB-FUEL CO	CALCULATED GRAMS/LB-FUEL NOX	CALCULATED GRAMS/BHP-HR HC	CALCULATED GRAMS/BHP-HR CO	CALCULATED GRAMS/BHP-HR NOX	F/A DRY MEAS	F/A STOICH	"PHI"	WET HC CORR FACT	F/A CALC	F/A PCT MEAS	POWER CORR FACT	BSFC CORR LB/HP-HR	MODAL WEIGHT FACTOR	MODE
1	10.01	17.58	27.76	*************		******	.0076	.0691	.110	.984	.0069	-10.0	.996	*****	.067	1
2	7.36	11.03	15.48	21.36	32.00	44.90	.0097	.0691	.140	.978	.0100	3.0	1.002	2.894	.080	2
3	3.58	5.09	17.38	1.69	2.40	8.19	.0197	.0691	.284	.960	.0199	1.1	1.002	.470	.080	3
4	2.02	2.15	20.27	.79	.84	7.90	.0292	.0691	.422	.943	.0293	.5	1.006	.388	.080	4
5	1.50	2.69	23.26	.55	.99	8.61	.0368	.0691	.532	.930	.0370	.6	1.010	.366	.080	5
6	.87	6.69	22.06	.32	2.49	8.21	.0433	.0691	.626	.919	.0435	.5	1.016	.366	.080	6
7	10.86	16.26	27.98	*************		******	.0065	.0691	.094	.984	.0067	2.7	.999	*****	.067	7
8	.61	9.12	21.61	.25	3.73	8.85	.0395	.0691	.571	.927	.0390	-1.3	1.061	.386	.080	8
9	1.05	3.61	21.91	.43	1.46	8.86	.0339	.0691	.491	.936	.0336	-.8	1.047	.386	.080	9
10	1.41	1.98	18.88	.63	.88	8.40	.0286	.0691	.414	.945	.0282	-1.5	1.038	.428	.080	10
11	2.65	3.76	15.23	1.52	2.16	8.76	.0214	.0691	.309	.958	.0211	-1.4	1.030	.559	.080	11
12	6.14	8.07	11.67	23.80	31.28	45.23	.0128	.0691	.185	.973	.0126	-1.2	1.023	3.789	.080	12
13	10.46	17.17	26.51	*************		******	.0072	.0691	.104	.985	.0067	-7.2	1.002	*****	.067	13

CYCLE COMPOSITE USING 13-MODE WEIGHT FACTORS
BSHC ------- = .799 GRAM/BHP-HR
BSCO ------- = 2.411 GRAM/BHP-HR
BSNOX ------ = 9.019 GRAM/BHP-HR
BSHC + BSNOX = 9.818 GRAM/BHP-HR
CORR. BSFC - = .429 LBS/BHP-HR

TABLE A-2

7-MODE DIESEL EMISSION CYCLE

ENGINE: IH DT466B DF-2 CONTROL FUEL H/C = 1.78 BAROMETER: 29.32
TEST-01-01 FUEL: EM-528-F PROJECT: 03-7338-004 DATE: 2/9/84

MODE	POWER PCT	ENGINE SPEED COND / RPM	TORQUE OBS LB-FT	POWER OBS BHP	FUEL FLOW LB/MIN	AIR FLOW LB/MIN	INTAKE HUMID GR/LB	NOX CORR FACT	MEASURED HC PPM	MEASURED CO PPM	MEASURED CO2 PCT	MEASURED NOX PPM	CALCULATED GRAMS / HOUR HC	CALCULATED GRAMS / HOUR CO	CALCULATED GRAMS / HOUR NOX	MODE
1	2	INTER / 1800.	9.	3.0	.145	15.16	80.	1.012	335.	253.	2.05	215.	64.	96.	135.	1
2	50	INTER / 1800.	222.	76.2	.495	17.16	80.	1.010	265.	148.	6.28	845.	60.	64.	602.	2
3	100	INTER / 1800.	445.	152.4	.945	22.09	82.	1.012	167.	691.	9.42	1380.	49.	379.	1251.	3
4		IDLE / 699.	0.	.0	.040	5.68	80.	.991	322.	263.	1.36	267.	25.	41.	67.	4
5	100	RATED / 2600.	431.	213.2	1.455	37.27	78.	1.004	105.	840.	8.38	1215.	53.	796.	1887.	5
6	50	RATED / 2600.	215.	106.6	.790	27.94	81.	.998	178.	131.	6.04	765.	67.	94.	895.	6
7	2	RATED / 2600.	9.	4.3	.280	22.15	81.	.992	353.	235.	2.62	210.	103.	136.	196.	7

MODE	CALCULATED GRAMS/LB-FUEL HC	CALCULATED GRAMS/LB-FUEL CO	CALCULATED GRAMS/LB-FUEL NOX	CALCULATED GRAMS/BHP-HR HC	CALCULATED GRAMS/BHP-HR CO	CALCULATED GRAMS/BHP-HR NOX	F/A DRY MEAS	F/A STOICH	"PHI"	WET HC CORR FACT	F/A CALC	F/A PCT MEAS	POWER CORR FACT	BSFC CORR LB/HP-HR	MODAL WEIGHT FACTOR	MODE
1	7.36	11.03	15.48	21.36	32.00	44.90	.0097	.0691	.140	.978	.0100	3.0	1.002	2.894	.120	1
2	2.02	2.15	20.27	.79	.84	7.90	.0292	.0691	.422	.943	.0293	.5	1.006	.388	.160	2
3	.87	6.69	22.06	.32	2.49	8.21	.0433	.0691	.626	.919	.0435	.5	1.016	.366	.120	3
4	10.46	17.05	27.99	******	******	******	.0071	.0691	.103	.984	.0067	-5.5	.999	*****	.200	4
5	.61	9.12	21.61	.25	3.73	8.85	.0395	.0691	.571	.927	.0390	-1.3	1.061	.386	.120	5
6	1.41	1.98	18.88	.63	.88	8.40	.0286	.0691	.414	.945	.0282	-1.5	1.038	.428	.160	6
7	6.14	8.07	11.67	23.80	31.28	45.23	.0128	.0691	.185	.973	.0126	-1.2	1.023	3.789	.120	7

CYCLE COMPOSITE USING 7-MODE WEIGHT FACTORS
BSHC ------- = .778 GRAM/BHP-HR
BSCO ------- = 2.733 GRAM/BHP-HR
BSNOX ------ = 9.042 GRAM/BHP-HR
BSHC + BSNOX = 9.820 GRAM/BHP-HR
CORR. BSFC - = .433 LBS/BHP-HR

TABLE A-3. SUPPLEMENTARY ENGINE DATA OBTAINED OVER 13-MODE TESTING ON (EM-528-F) DF-2

Test Mode No.	Fuel			Inlet Air			Exhaust		Oil	
	Temp.[a] °F	Press.[b] psi	Injector Temp.[c] °F	Temp. °F	Restrict. in. H_2O	Boost psi	Temp. °F	B.P. in. Hg	Temp. °F	Press. psi
1	97	31.0	109	89	1.2	0	288	0.05	d	25
2	96	50.5	111	86	5.1	0.5	332	0.2	d	50
3	96	49.5	117	85	5.5	1.1	502	0.25	d	49
4	97	48.5	123	86	6.3	3.0	690	0.3	d	48
5	96	47.5	127	87	7.6	5.7	848	0.4	d	47
6	96	46.5	128	88	9.5	9.3	1013	0.6	d	45
7	99	31.5	121	91	1.2	0	475	0.05	d	23
8	96	57.0	143	89	25.0	17.4	1051	2.0	d	49
9	99	59.0	149	92	18.8	11.2	920	1.3	d	48.5
10	100	61.0	147	93	14.9	6.9	797	0.9	d	49
11	101	62.0	141	93	11.6	3.4	658	0.6	d	50
12	101	63.5	137	92	9.6	1.4	491	0.4	d	51.5
13	100	31.0	124	92	1.2	0	325	0.05	d	23

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[a] Measured at fuel inlet to pump

[b] Measured after secondary filter

[c] Measured approximately 2 inches upstream of injector No. 1

[d] No data

TABLE A-4
TRANSIENT ENGINE MAP DATA

Engine Model DT-466B Date 2/27/84 Barometer 29.2 in. Hg

Engine Intake Air 77 °F, Relative Humidity 38 %

Transient Map Results

Speed, rpm	Torque, ft-lb[a]	Speed, rpm	Torque, ft-lb[a]
100	139	2300	440
200	139	2400	434
300	139	2500	424
400	139	2600	416
500	139	2700	386
600	155	2800	260
700	189	2900	0
800	210	3000	0
900	232	3100	0
1000	251	3200	0
1100	263	3300	0
1200	267	3400	0
1300	276	3500	0
1400	300	3600	0
1500	338	3700	0
1600	401	3800	0
1700	408	3900	0
1800	414	4000	0
1900	419	4100	0
2000	432	4200	0
2100	454	4300	0
2200	446	4400	0

Idle Speed 650 rpm

Max. Power 206 hp (416 ft-lb) @ 2600 rpm

Max. Torque 454 ft-lb @ 2100 rpm

Transient Cycle Work by Command, hp-hr

Segment 1	Segment 2	Segment 3	Segment 4	Total
1.35	2.54	7.63	1.34	12.86

TABLE A-5

13-MODE FEDERAL DIESEL EMISSION CYCLE 1979

ENGINE: IH 466 H/C 1.78 BAROMETER: 29.18
TEST-1 FUEL: EM-528-F PROJECT: 03-7338-004 DATE: 3/13/84

MODE	POWER PCT	ENGINE SPEED COND / RPM	TORQUE OBS LB-FT	POWER OBS BHP	FUEL FLOW LB/MIN	AIR FLOW LB/MIN	INTAKE HUMID GR/LB	NOX CORR FACT	MEASURED HC PPM	MEASURED CO PPM	MEASURED CO2 PCT	MEASURED NOX PPM	CALCULATED GRAMS / HOUR HC	CALCULATED GRAMS / HOUR CO	CALCULATED GRAMS / HOUR NOX	MODE
1		IDLE / 618.	0.	.0	.032	4.85	71.	.975	260.	258.	1.38	340.	16.	31.	66.	1
2	2	INTER / 1800.	9.	3.1	.145	15.26	71.	1.001	315.	258.	1.94	200.	64.	103.	131.	2
3	25	INTER / 1800.	100.	34.3	.288	15.61	71.	1.002	293.	269.	3.85	430.	61.	110.	286.	3
4	50	INTER / 1800.	200.	68.5	.460	16.84	71.	.999	283.	191.	5.94	700.	63.	81.	484.	4
5	75	INTER / 1800.	301.	103.2	.640	18.54	70.	.991	258.	213.	7.51	1025.	64.	100.	775.	5
6	100	INTER / 1800.	400.	137.1	.847	21.16	70.	.990	218.	457.	8.68	1188.	62.	244.	1025.	6
7		IDLE / 618.	0.	.0	.030	4.83	70.	.965	270.	247.	1.34	325.	16.	29.	61.	7
8	100	RATED / 2600.	400.	198.0	1.380	36.16	70.	.991	158.	667.	8.28	1100.	76.	607.	1620.	8
9	75	RATED / 2600.	300.	148.5	1.040	31.48	70.	.991	215.	269.	7.14	950.	90.	215.	1227.	9
10	50	RATED / 2600.	201.	99.5	.763	28.15	70.	.993	220.	147.	5.86	695.	82.	105.	805.	10
11	25	RATED / 2600.	101.	50.0	.508	24.61	70.	.991	265.	191.	4.45	440.	85.	119.	444.	11
12	2	RATED / 2600.	8.	4.0	.327	22.88	70.	.991	333.	235.	2.88	230.	104.	144.	228.	12
13		IDLE / 615.	0.	.0	.033	4.81	70.	.970	305.	247.	1.38	320.	20.	32.	65.	13

MODE	CALCULATED GRAMS/LB-FUEL HC	CALCULATED GRAMS/LB-FUEL CO	CALCULATED GRAMS/LB-FUEL NOX	CALCULATED GRAMS/BHP-HR HC	CALCULATED GRAMS/BHP-HR CO	CALCULATED GRAMS/BHP-HR NOX	F/A DRY MEAS	F/A STOICH	"PHI"	WET HC CORR FACT	F/A CALC	F/A PCT MEAS	POWER CORR FACT	BSFC CORR LB/HP-HR	MODAL WEIGHT FACTOR	MODE
1	8.37	16.57	34.74	************		******	.0066	.0691	.095	.984	.0068	2.8	1.000	*****	.067	1
2	7.30	11.88	15.04	20.59	33.51	42.41	.0096	.0691	.139	.980	.0094	-1.6	1.004	2.810	.080	2
3	3.53	6.33	16.55	1.78	3.20	8.36	.0187	.0691	.270	.964	.0183	-1.9	1.003	.503	.080	3
4	2.26	2.93	17.53	.91	1.18	7.06	.0276	.0691	.399	.946	.0278	.8	1.005	.401	.080	4
5	1.66	2.59	20.17	.62	.96	7.51	.0349	.0691	.504	.934	.0349	.0	1.011	.368	.080	5
6	1.22	4.81	20.18	.45	1.78	7.48	.0404	.0691	.585	.925	.0402	-.6	1.017	.364	.080	6
7	8.93	16.32	33.81	************		******	.0063	.0691	.091	.985	.0066	5.1	1.001	*****	.067	7
8	.92	7.34	19.57	.39	3.07	8.18	.0385	.0691	.558	.928	.0385	-.2	1.058	.395	.080	8
9	1.45	3.44	19.66	.61	1.45	8.26	.0334	.0691	.483	.937	.0332	-.4	1.042	.403	.080	9
10	1.79	2.29	17.57	.82	1.06	8.09	.0274	.0691	.396	.947	.0274	.0	1.031	.447	.080	10
11	2.79	3.91	14.56	1.70	2.38	8.88	.0209	.0691	.302	.959	.0210	.8	1.024	.596	.080	11
12	5.29	7.36	11.65	26.18	36.42	57.65	.0144	.0691	.209	.972	.0138	-4.1	1.019	4.856	.080	12
13	9.79	15.83	32.44	************		******	.0070	.0691	.101	.985	.0068	-2.8	1.001	*****	.067	13

CYCLE COMPOSITE USING 13-MODE WEIGHT FACTORS
BSHC ------- = .938 GRAM/BHP-HR
BSCO ------- = 2.252 GRAM/BHP-HR
BSNOX ------ = 8.491 GRAM/BHP-HR
BSHC + BSNOX = 9.429 GRAM/BHP-HR
CORR. BSFC - = .446 LBS/BHP-HR

TABLE A-6. SUPPLEMENTARY ENGINE DATA OBTAINED OVER 13-MODE TESTING ON (EM-528-F) DF-2

Test	Fuel			Inlet Air			Exhaust		Oil	
Mode No.	Temp.[a] ° F	Press.[b] psi	Injector Temp.[c] °F	Temp. °F	Restrict. in. H_2O	Boost psi	Temp. °F	B.P. in. Hg	Temp. °F	Press. psi
1	99	29.0	132	88	1.0	—	342	—	199	19
2	99	50.0	123	82	5.6	0.6	343	0.2	196	48
3	98	49.5	130	81	5.9	1.2	491	0.3	199	48
4	98	48.5	133	81	6.6	2.7	665	0.4	204	47
5	98	47.5	136	83	7.8	4.9	924	0.6	208	46
6	97	46.5	136	84	9.6	7.9	968	0.8	212	44
7	100	29.0	140	89	1.0	—	363	—	193	20
8	96	56.5	149	83	24.8	15.3	1054	2.7	222	51
9	98	58.5	155	83	19.3	10.4	920	1.9	228	47
10	99	60.0	155	82	15.5	6.6	792	1.4	223	48
11	100	62.0	151	83	12.5	3.5	648	0.9	217	48
12	100	63.0	153	83	10.7	1.7	505	0.7	213	49
13	101	28.5	141	88	1.0	—	276	—	192	20

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[a] Measured at fuel inlet to pump

[b] Measured after secondary filter

[c] Measured approximately 2 inches upstream of injector No. 1

TABLE A-7. REGULATED EMISSIONS SUMMARY FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-528-F) DF-2

Test No.	Run No.	Transient Emissions, g/kW-hr (g/hp-hr) HC	CO	NO_x	Part.	Cycle BSFC kg/kW-hr (lb/hp-hr)	Cycle Work[c] kW-hr (hp-hr)
1	1	1.17 (0.87)	2.75 (2.05)	10.25 (7.64)	0.94 (0.70)[a]	0.252 (0.414)	9.34 (12.53)
1	2	1.25 (0.93)	3.27 (2.44)	11.26 (8.40)	0.94 (0.70)[a]	0.284 (0.467)	9.34 (12.53)
1	3	1.21 (0.90)	3.22 (2.40)	10.86 (8.10)	0.94 (0.70)[a]	0.270 (0.444)	9.35 (12.54)
1	4	1.29 (0.96)	3.19 (2.38)	11.35 (8.46)	0.97 (0.72)[b]	0.272 (0.448)	9.35 (12.54)
1	5	1.34 (1.00)	3.10 (2.31)	11.08 (8.26)	0.97 (0.72)[b]	0.268 (0.441)	9.35 (12.54)
1	6	1.37 (1.02)	3.22 (2.40)	11.48 (8.56)	0.97 (0.72)[b]	0.276 (0.454)	9.35 (12.54)

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[a] Based on particulate samples obtained using one set of filters over 3 consecutive runs (1,2,3)

[b] Based on particulate samples obtained using one set of filters over 3 consecutive runs (4,5,6)

[c] All runs met statistical criteria for transient FTP

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                         TABLE A-8.  ENGINE EMISSION RESULTS
                                          H-TRANS.                                   PROJECT NO. 03-7338-004

ENGINE  NO.1                                TEST NO.1       RUN1
ENGINE  MODEL     0 IHC DT466B              DATE  3/12/84
ENGINE  7.6 L(466. CID) L-6                 TIME                               DIESEL   EM-528-F
CVS NO.  11                                 DYNO NO.  1                        BAG CART NO.  1

BAROMETER 738.12 MM HG(29.06 IN HG)         RELATIVE HUMIDITY ,  ENGINE-58. PCT ,  CVS-59. PCT
DRY BULB TEMP. 25.6 DEG C(78.0 DEG F)       ABSOLUTE HUMIDITY 12.3 GM/KG( 86.0 GRAINS/LB)      NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                      1                2                3                4
  DESCRIPTION                                   NYNF             LANF              LAF             NYNF
  TIME SECONDS                                  296.0            300.0            305.0            298.0
  TOT. BLOWER RATE SCMM (SCFM)             82.61 ( 2916.8)  82.61 ( 2917.0)  82.59 ( 2916.2)  82.57 ( 2915.7)
  TOT. 20X20 RATE SCMM (SCFM)               9.18 (324.1)     9.18 (324.1)     9.18 (324.1)     9.18 (324.1)
  TOT. 90MM RATE SCMM (SCFM)                 .03 ( 1.01)      .03 ( 1.01)      .03 ( 1.01)      .03 ( 1.01)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)          .05 ( 1.75)      .05 ( 1.75)      .05 ( 1.75)      .05 ( 1.75)
  TOTAL FLOW STD. CU. METRES(SCF)         453.2 (  16002.)  459.3 (16219.)   466.9 (16485.)   456.1 (16105.)

  HC  SAMPLE METER/RANGE/PPM              28.7/21/  14.    35.5/21/  18.    50.2/21/  25.    32.9/21/  16.
  HC  BCKGRD METER/RANGE/PPM              15.5/ 1/   8.    16.7/ 1/   8.    17.0/ 1/   9.    17.0/ 1/   9.
  CO  SAMPLE METER/RANGE/PPM              13.1/13/  12.    17.6/13/  16.    24.2/13/  22.    11.3/13/  10.
  CO  BCKGRD METER/RANGE/PPM               3.9/13/   4.     3.3/13/   3.     2.7/13/   2.     2.6/13/   2.
  CO2 SAMPLE METER/RANGE/PCT              73.3/13/  .15    57.2/12/  .23    63.8/11/  .54    66.2/13/  .13
  CO2 BCKGRD METER/RANGE/PCT              23.7/13/  .04    13.0/12/  .04     7.7/11/  .05    24.2/13/  .04
  NOX SAMPLE METER/RANGE/PPM              50.4/ 1/  15.    72.6/ 1/  22.    61.5/ 2/  62.    43.1/ 1/  13.
  NOX BCKGRD METER/RANGE/PPM               2.4/ 1/   1.     2.5/ 1/   1.      .6/ 2/   1.     2.0/ 1/   1.

  DILUTION FACTOR                              87.49            57.89            24.67            97.93
  HC  CONCENTRATION PPM                          7.              10.              17.               8.
  CO  CONCENTRATION PPM                          8.              13.              19.               8.
  CO2 CONCENTRATION PCT                          .11              .18              .49              .09
  NOX CONCENTRATION PPM                        14.3             20.9             60.9             12.2

  HC  MASS GRAMS                                1.75             2.53             4.57             2.11
  CO  MASS GRAMS                                4.32             6.82            10.42             4.10
  CO2 MASS GRAMS                               888.9           1552.5           4223.2            749.0
  NOX MASS GRAMS                               12.38            18.33            54.40            10.67
  FUEL KG (LB)                             .283 (     .62)  .494 (    1.09)  1.336 (    2.95)  .239 (     .53)
  KW HR (HP HR)                            1.00 (    1.34)  1.80 (    2.42)  5.54 (     7.43)  1.00 (    1.34)

  BSHC G/KW HR (G/HP HR)                   1.75 (    1.30)  1.40 (    1.05)   .82 (     .61)  2.12 (    1.58)
  BSCO G/KW HR (G/HP HR)                   4.33 (    3.23)  3.78 (    2.82)  1.88 (    1.40)  4.10 (    3.06)
  BSCO2 G/KW HR (G/HP HR)                889.56 ( 663.34) 860.32 ( 641.54) 762.23 ( 568.40) 749.60 ( 558.98)
  BSNOX G/KW HR (G/HP HR)                 12.39 (    9.24) 10.16 (    7.57)  9.82 (    7.32) 10.68 (    7.96)
  BSFC KG/KW HR (LB/HP HR)                 .283 (    .466)  .274 (    .450)  .241 (    .397)  .240 (    .394)

 TOTAL TEST RESULTS 4 BAGS                             PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)          9.34 ( 12.53)        90MM PARTICULATE RATES    GRAMS/TEST                  8.74
  BSHC  G/KW HR (G/HP HR)      1.17 (   .87)                                  G/KWHR(G/HPHR)          .94  (  .70)
  BSCO  G/KW HR (G/HP HR)      2.75 (  2.05)                                  G/KG FUEL (G/LB FUEL)  3.72  ( 1.69)
  BSCO2 G/KW HR (G/HP HR)      793. (  592.)                                  FILTER EFF.                 97.6
  BSNOX G/KW HR (G/HP HR)     10.25 (  7.64)
  BSFC  KG/KW HR (LB/HP HR)    .252 (  .414)
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TABLE A-9. ENGINE EMISSION RESULTS
H-TRANS.

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                                                                                   PROJECT NO. 03-7338-004

ENGINE  NO.1                                   TEST NO.1      RUN2
ENGINE  MODEL     0 IHC DT466B                 DATE  3/12/84
ENGINE  7.6 L(466. CID) L-6                    TIME                           DIESEL   EM-528-F
CVS NO.  11                                    DYNO NO.  1                    BAG CART NO.  1

BAROMETER 738.12 MM HG(29.06 IN HG)            RELATIVE HUMIDITY ,  ENGINE-61. PCT ,  CVS-59. PCT
DRY BULB TEMP. 24.4 DEG C(76.0 DEG F)          ABSOLUTE HUMIDITY 12.1 GM/KG( 84.6 GRAINS/LB)    NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                        1                  2                  3                  4
  DESCRIPTION                                     NYNF               LANF               LAF                NYNF
  TIME SECONDS                                    296.0              300.0              305.0              298.0
  TOT. BLOWER RATE SCMM (SCFM)              82.43 ( 2910.5)    82.43 ( 2910.6)    82.43 ( 2910.5)    82.39 ( 2909.3)
  TOT. 20X20 RATE SCMM (SCFM)                9.18 (324.1)       9.18 (324.1)       9.18 (324.1)       9.18 (324.1)
  TOT. 90MM RATE SCMM (SCFM)                  .03 ( 1.01)        .03 ( 1.01)        .03 ( 1.01)        .03 ( 1.01)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)           .05 ( 1.75)        .05 ( 1.75)        .05 ( 1.75)        .05 ( 1.75)
  TOTAL FLOW STD. CU. METRES(SCF)           452.3 (  15971.)   458.4 (16187.)     466.1 (16457.)     455.2 (16073.)

  HC   SAMPLE METER/RANGE/PPM               32.8/21/  16.      37.3/21/  19.      50.3/21/  25.      31.2/21/  16.
  HC   BCKGRD METER/RANGE/PPM               16.5/ 1/   8.      16.4/ 1/   8.      16.4/ 1/   8.      15.5/ 1/   8.
  CO   SAMPLE METER/RANGE/PPM               13.5/13/  12.      22.1/13/  20.      26.5/13/  24.      11.9/13/  11.
  CO   BCKGRD METER/RANGE/PPM                3.2/13/   3.       2.6/13/   2.       2.1/13/   2.       1.9/13/   2.
  CO2  SAMPLE METER/RANGE/PCT               76.4/13/  .16      70.2/12/  .29      65.7/11/  .56      73.3/13/  .15
  CO2  BCKGRD METER/RANGE/PCT               24.4/13/  .05      12.6/12/  .04       7.6/11/  .05      22.1/13/  .04
  NOX  SAMPLE METER/RANGE/PPM               52.7/ 1/  16.      94.2/ 1/  28.      63.5/ 2/  64.      49.9/ 1/  15.
  NOX  BCKGRD METER/RANGE/PPM                2.5/ 1/   1.       2.8/ 1/   1.        .6/ 2/   1.       1.9/ 1/   1.

  DILUTION FACTOR                              83.33              45.23              23.70              87.48
  HC   CONCENTRATION PPM                         8.                11.                17.                 8.
  CO   CONCENTRATION PPM                         9.                17.                22.                 9.
  CO2  CONCENTRATION PCT                         .11                .25                .52                .11
  NOX  CONCENTRATION PPM                       14.9               27.2               62.9               14.3

  HC   MASS GRAMS                               2.16               2.82               4.65               2.09
  CO   MASS GRAMS                               4.82               9.29              11.81               4.70
  CO2  MASS GRAMS                              937.1             2102.9             4410.5              919.0
  NOX  MASS GRAMS                              12.93              23.85              56.09              12.44
  FUEL KG (LB)                              .299 (     .66)   .668 (    1.47)  1.396 (    3.08)   .293 (     .65)
  KW HR (HP HR)                              .99 (    1.33)   1.80 (    2.42)   5.55 (    7.44)   1.00 (    1.34)

  BSHC G/KW HR (G/HP HR)                    2.17 (    1.62)   1.56 (    1.16)    .84 (     .62)   2.09 (    1.56)
  BSCO G/KW HR (G/HP HR)                    4.86 (    3.63)   5.15 (    3.84)   2.13 (    1.59)   4.70 (    3.51)
  BSCO2 G/KW HR (G/HP HR)                 944.92 ( 704.62) 1165.28 ( 868.95) 794.97 ( 592.81) 919.75 ( 685.86)
  BSNOX G/KW HR (G/HP HR)                  13.03 (    9.72)  13.22 (    9.86)  10.11 (    7.54)  12.45 (    9.28)
  BSFC KG/KW HR (LB/HP HR)                  .301 (    .496)   .370 (    .609)   .252 (    .414)   .293 (    .482)

 TOTAL TEST RESULTS 4 BAGS                        PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)          9.34 ( 12.53)      90MM PARTICULATE RATES    GRAMS/TEST                   8.73
  BSHC   G/KW HR (G/HP HR)     1.25 (   .93)                                G/KWHR(G/HPHR)             .93  (  .70)
  BSCO   G/KW HR (G/HP HR)     3.28 (  2.44)                                G/KG FUEL (G/LB FUEL)     3.29  ( 1.49)
  BSCO2  G/KW HR (G/HP HR)     896. (  668.)                                FILTER EFF.                  97.6
  BSNOX  G/KW HR (G/HP HR)    11.27 (  8.40)
  BSFC   KG/KW HR (LB/HP HR)   .284 (  .467)
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TABLE A-10. ENGINE EMISSION RESULTS

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                                  TABLE A-10. ENGINE EMISSION RESULTS
                                              H-TRANS.                               PROJECT NO. 03-7338-004

ENGINE  NO.1                               TEST NO.1       RUN3
ENGINE  MODEL     0 IHC DT466B             DATE  3/12/84
ENGINE  7.6 L(466. CID) L-6                TIME                                 DIESEL   EM-528-F
CVS NO.  11                                DYNO NO.  1                          BAG CART NO.  1

BAROMETER 738.12 MM HG(29.06 IN HG)        RELATIVE HUMIDITY ,  ENGINE-63. PCT ,  CVS-53. PCT
DRY BULB TEMP. 23.9 DEG C(75.0 DEG F)      ABSOLUTE HUMIDITY 12.1 GM/KG( 84.5 GRAINS/LB)     NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                     1                2                3                4
  DESCRIPTION                                  NYNF             LANF              LAF             NYNF
  TIME SECONDS                                296.0            300.0            305.0            298.0
  TOT. BLOWER RATE SCMM (SCFM)         82.55 ( 2914.8)  82.55 ( 2914.9)  82.56 ( 2915.2)  82.55 ( 2915.0)
  TOT. 20X20 RATE SCMM (SCFM)           9.18 (324.1)     9.18 (324.1)     9.18 (324.1)     9.18 (324.1)
  TOT. 90MM RATE SCMM (SCFM)             .03 ( 1.01)      .03 ( 1.01)      .03 ( 1.01)      .03 ( 1.01)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)      .05 ( 1.75)      .05 ( 1.75)      .05 ( 1.75)      .05 ( 1.75)
  TOTAL FLOW STD. CU. METRES(SCF)      452.9 ( 15992.)  459.0 (16209.)   466.7 (16480.)   456.0 (16101.)

  HC   SAMPLE METER/RANGE/PPM          30.1/21/  15.    35.3/21/  18.    48.2/21/  24.    31.4/21/  16.
  HC   BCKGRD METER/RANGE/PPM          15.4/ 1/   8.    15.4/ 1/   8.    15.4/ 1/   8.    15.4/ 1/   8.
  CO   SAMPLE METER/RANGE/PPM          12.9/13/  12.    18.1/13/  16.    26.9/13/  25.    11.9/13/  11.
  CO   BCKGRD METER/RANGE/PPM           1.8/13/   2.     1.8/13/   2.     1.5/13/   1.     1.6/13/   1.
  CO2  SAMPLE METER/RANGE/PCT          74.3/13/  .15    58.4/12/  .23    65.5/11/  .56    77.1/13/  .16
  CO2  BCKGRD METER/RANGE/PCT          21.8/13/  .04    12.4/12/  .04     7.2/11/  .04    22.5/13/  .04
  NOX  SAMPLE METER/RANGE/PPM          50.8/ 1/  15.    74.5/ 1/  22.    63.7/ 2/  64.    54.1/ 1/  16.
  NOX  BCKGRD METER/RANGE/PPM           1.8/ 1/   1.     1.9/ 1/   1.      .6/ 2/   1.     1.7/ 1/   0.

  DILUTION FACTOR                           86.13            56.49            23.80            82.57
  HC   CONCENTRATION PPM                     7.              10.              17.               8.
  CO   CONCENTRATION PPM                    10.              15.              23.               9.
  CO2  CONCENTRATION PCT                    .11              .19              .52              .12
  NOX  CONCENTRATION PPM                   14.6             21.6             63.1             15.6

  HC   MASS GRAMS                           1.94             2.67             4.50             2.13
  CO   MASS GRAMS                           5.20             7.76            12.33             4.86
  CO2  MASS GRAMS                          939.0           1617.5           4417.3            990.3
  NOX  MASS GRAMS                          12.63            18.97            56.34            13.60
  FUEL KG (LB)                        .299 (    .66)  .515 (   1.13)  1.398 (   3.08)  .316 (    .70)
  KW HR (HP HR)                       1.00 (   1.34)  1.80 (   2.42)  5.55 (   7.44)  1.00 (   1.34)

  BSHC G/KW HR (G/HP HR)              1.95 (   1.45)  1.48 (   1.10)   .81 (    .61)  2.13 (   1.59)
  BSCO G/KW HR (G/HP HR)              5.21 (   3.88)  4.30 (   3.21)  2.22 (   1.66)  4.86 (   3.62)
  BSCO2 G/KW HR (G/HP HR)           939.69 ( 700.73) 896.30 ( 668.37) 796.19 ( 593.72) 991.01 ( 739.00)
  BSNOX G/KW HR (G/HP HR)            12.64 (   9.43) 10.51 (   7.84)  10.16 (   7.57)  13.61 (  10.15)
  BSFC KG/KW HR (LB/HP HR)            .300 (   .493)  .285 (   .469)  .252 (   .414)  .316 (   .519)

 TOTAL TEST RESULTS 4 BAGS                        PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)          9.35 ( 12.54)     90MM PARTICULATE RATES   GRAMS/TEST                   8.74
  BSHC  G/KW HR (G/HP HR)      1.20 (   .90)                              G/KWHR(G/HPHR)           .93  (  .70)
  BSCO  G/KW HR (G/HP HR)      3.22 (  2.40)                              G/KG FUEL (G/LB FUEL)   3.46  ( 1.57)
  BSCO2 G/KW HR (G/HP HR)      852. (  635.)                              FILTER EFF.                  97.6
  BSNOX G/KW HR (G/HP HR)     10.86 (  8.10)
  BSFC  KG/KW HR (LB/HP HR)    .270 (  .444)
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TABLE A-11. ENGINE EMISSION RESULTS
H-TRANS.

PROJECT NO. 03-7338-004

ENGINE NO.1
ENGINE MODEL 0 IHC DT466B
ENGINE 7.6 L(466. CID) L-4
CVS NO. 11

TEST NO.1 RUN4
DATE 3/12/84
TIME
DYNO NO. 1

DIESEL EM-528-F
BAG CART NO. 1

BAROMETER 737.36 MM HG(29.03 IN HG)
DRY BULB TEMP. 25.0 DEG C(77.0 DEG F)

RELATIVE HUMIDITY , ENGINE-51. PCT , CVS-52. PCT
ABSOLUTE HUMIDITY 10.3 GM/KG(72.3 GRAINS/LB) NOX HUMIDITY C.F. 1.0000

BAG RESULTS				
BAG NUMBER	1	2	3	4
DESCRIPTION	NYNF	LANF	LAF	NYNF
TIME SECONDS	296.0	300.0	305.0	298.0
TOT. BLOWER RATE SCMM (SCFM)	82.36 (2908.2)	82.35 (2907.9)	82.36 (2908.2)	82.34 (2907.4)
TOT. 20X20 RATE SCMM (SCFM)	9.12 (321.9)	9.12 (321.9)	9.12 (321.9)	9.12 (321.9)
TOT. 90MM RATE SCMM (SCFM)	.03 (.99)	.03 (.99)	.03 (.99)	.03 (.99)
TOT. AUX. SAMPLE RATE SCMM (SCFM)	.05 (1.71)	.05 (1.71)	.05 (1.71)	.05 (1.71)
TOTAL FLOW STD. CU. METRES(SCF)	451.7 (15948.)	457.7 (16163.)	465.4 (16433.)	454.6 (16052.)
HC SAMPLE METER/RANGE/PPM	28.1/21/ 14.	33.5/21/ 17.	47.8/21/ 24.	31.3/21/ 16.
HC BCKGRD METER/RANGE/PPM	12.0/ 1/ 6.	12.7/ 1/ 6.	13.0/ 1/ 7.	13.4/ 1/ 7.
CO SAMPLE METER/RANGE/PPM	10.8/13/ 10.	16.5/13/ 15.	27.0/13/ 25.	9.4/13/ 8.
CO BCKGRD METER/RANGE/PPM	.2/13/ 0.	.3/13/ 0.	.2/13/ 0.	.3/13/ 0.
CO2 SAMPLE METER/RANGE/PCT	77.9/13/ .16	58.9/12/ .24	66.0/11/ .56	71.2/13/ .15
CO2 BCKGRD METER/RANGE/PCT	21.1/13/ .04	11.5/12/ .04	7.0/11/ .04	21.8/13/ .04
NOX SAMPLE METER/RANGE/PPM	57.3/ 1/ 17.	78.8/ 1/ 23.	66.8/ 2/ 67.	47.0/ 1/ 14.
NOX BCKGRD METER/RANGE/PPM	.6/ 1/ 0.	.6/ 1/ 0.	.4/ 2/ 0.	.5/ 1/ 0.
DILUTION FACTOR	81.72	55.98	23.55	90.51
HC CONCENTRATION PPM	8.	11.	18.	9.
CO CONCENTRATION PPM	9.	14.	24.	8.
CO2 CONCENTRATION PCT	.12	.20	.52	.11
NOX CONCENTRATION PPM	16.9	23.3	66.4	13.8
HC MASS GRAMS	2.12	2.78	4.75	2.37
CO MASS GRAMS	4.94	7.67	12.94	4.27
CO2 MASS GRAMS	1019.6	1659.3	4465.2	881.7
NOX MASS GRAMS	14.57	20.37	59.11	12.03
FUEL KG (LB)	.325 (.72)	.528 (1.16)	1.414 (3.12)	.281 (.62)
KW HR (HP HR)	1.00 (1.34)	1.82 (2.44)	5.53 (7.42)	1.00 (1.34)
BSHC G/KW HR (G/HP HR)	2.12 (1.58)	1.53 (1.14)	.86 (.64)	2.37 (1.77)
BSCO G/KW HR (G/HP HR)	4.94 (3.69)	4.22 (3.14)	2.34 (1.74)	4.27 (3.18)
BSCO2 G/KW HR (G/HP HR)	1020.42 (760.92)	911.96 (680.05)	806.99 (601.77)	882.33 (657.95)
BSNOX G/KW HR (G/HP HR)	14.58 (10.87)	11.19 (8.35)	10.68 (7.97)	12.04 (8.98)
BSFC KG/KW HR (LB/HP HR)	.325 (.534)	.290 (.477)	.256 (.420)	.282 (.463)

TOTAL TEST RESULTS 4 BAGS

TOTAL KW HR (HP HR)	9.35 (12.54)
BSHC G/KW HR (G/HP HR)	1.28 (.96)
BSCO G/KW HR (G/HP HR)	3.19 (2.38)
BSCO2 G/KW HR (G/HP HR)	858. (640.)
BSNOX G/KW HR (G/HP HR)	11.34 (8.46)
BSFC KG/KW HR (LB/HP HR)	.272 (.448)

PARTICULATE RESULTS, TOTAL FOR 4 BAGS

90MM PARTICULATE RATES		
	GRAMS/TEST	9.02
	G/KWHR(G/HPHR)	.97 (.72)
	G/KG FUEL (G/LB FUEL)	3.54 (1.61)
	FILTER EFF.	97.9

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                              TABLE A-12. ENGINE EMISSION RESULTS
                                          H-TRANS.                                   PROJECT NO. 03-7338-004

ENGINE  NO.1                                TEST NO.1      RUN5
ENGINE  MODEL     0 IHC DT466B              DATE  3/12/84
ENGINE  7.6 L(466. CID) L-6                 TIME                               DIESEL    EM-528-F
CVS NO.  11                                 DYNO NO.  1                        BAG CART NO.  1

BAROMETER 737.11 MM HG(29.02 IN HG)         RELATIVE HUMIDITY ,  ENGINE-52. PCT ,  CVS-52. PCT
DRY BULB TEMP. 24.4 DEG C(76.0 DEG F)       ABSOLUTE HUMIDITY 10.2 GM/KG( 71.3 GRAINS/LB)     NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                     1                  2                  3                  4
  DESCRIPTION                                  NYNF               LANF                LAF               NYNF
  TIME SECONDS                                296.0              300.0              305.0              298.0
  TOT. BLOWER RATE SCMM (SCFM)         82.05 ( 2897.4)    82.05 ( 2897.1)    82.06 ( 2897.4)    82.18 ( 2901.6)
  TOT. 20X20 RATE SCMM (SCFM)           9.11 (321.7)       9.11 (321.7)       9.11 (321.7)       9.11 (321.7)
  TOT. 90MM RATE SCMM (SCFM)             .03 (   .99)       .03 (   .99)       .03 (   .99)       .03 (   .99)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)      .05 ( 1.71)        .05 ( 1.71)        .05 ( 1.71)        .05 ( 1.71)
  TOTAL FLOW STD. CU. METRES(SCF)      450.1 (  15894.)   456.2 (16108.)     463.8 (16378.)     453.8 (16023.)

  HC   SAMPLE METER/RANGE/PPM          31.2/21/  16.      36.3/21/  18.      49.6/21/  25.      30.0/21/  15.
  HC   BCKGRD METER/RANGE/PPM          13.5/ 1/   7.      13.6/ 1/   7.      13.4/ 1/   7.      12.4/ 1/   6.
  CO   SAMPLE METER/RANGE/PPM          10.8/13/  10.      15.8/13/  14.      25.7/13/  24.       9.7/13/   9.
  CO   BCKGRD METER/RANGE/PPM            .2/13/   0.        .4/13/   0.        .2/13/   0.        .1/13/   0.
  CO2 SAMPLE METER/RANGE/PCT           75.1/13/  .15      57.7/12/  .23      65.9/11/  .56      73.5/13/  .15
  CO2 BCKGRD METER/RANGE/PCT           22.1/13/  .04      12.2/12/  .04       7.0/11/  .04      21.4/13/  .04
  NOX  SAMPLE METER/RANGE/PPM          54.0/ 1/  16.      75.4/ 1/  22.      65.5/ 2/  66.      50.4/ 1/  15.
  NOX  BCKGRD METER/RANGE/PPM            .9/ 1/   0.       1.2/ 1/   0.        .3/ 2/   0.        .5/ 1/   0.

  DILUTION FACTOR                          85.15              57.33              23.60              87.35
  HC   CONCENTRATION PPM                    9.                11.                18.                 9.
  CO   CONCENTRATION PPM                    9.                14.                23.                 9.
  CO2 CONCENTRATION PCT                     .11                .19                .52                .11
  NOX CONCENTRATION PPM                    15.8               22.1               65.2               14.8

  HC   MASS GRAMS                           2.32               3.02               4.92               2.32
  CO   MASS GRAMS                           4.92               7.27              12.26               4.49
  CO2 MASS GRAMS                          944.1             1585.2             4440.0              931.5
  NOX MASS GRAMS                           13.60              19.26              57.84              12.88
  FUEL KG (LB)                         .301 (    .66)    .505 (   1.11)    1.406 (   3.10)    .297 (     .66)
  KW HR (HP HR)                        1.00 (   1.34)    1.80 (   2.42)     5.55 (   7.44)    1.00 (    1.34)

  BSHC G/KW HR (G/HP HR)               2.32 (   1.73)    1.67 (   1.25)      .89 (    .66)    2.32 (    1.73)
  BSCO G/KW HR (G/HP HR)               4.93 (   3.67)    4.03 (   3.00)     2.21 (   1.65)    4.50 (    3.35)
  BSCO2 G/KW HR (G/HP HR)            944.86 ( 704.58)  878.45 ( 655.06)   800.29 ( 596.78)  932.18 ( 695.12)
  BSNOX G/KW HR (G/HP HR)             13.61 (  10.15)   10.67 (   7.96)    10.43 (   7.77)   12.89 (    9.61)
  BSFC KG/KW HR (LB/HP HR)             .302 (   .496)    .280 (   .460)     .253 (   .417)    .297 (    .489)

 TOTAL TEST RESULTS 4 BAGS                          PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)             9.35 ( 12.54)     90MM PARTICULATE RATES     GRAMS/TEST                  9.01
  BSHC  G/KW HR (G/HP HR)         1.34 (  1.00)                                G/KWHR(G/HPHR)           .96  (  .72)
  BSCO  G/KW HR (G/HP HR)         3.09 (  2.31)                                G/KG FUEL (G/LB FUEL)    3.59  ( 1.63)
  BSCO2 G/KW HR (G/HP HR)         845. (  630.)                                FILTER EFF.                97.9
  BSNOX G/KW HR (G/HP HR)        11.08 (  8.26)
  BSFC  KG/KW HR (LB/HP HR)       .268 (  .441)
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                         TABLE A-13. ENGINE EMISSION RESULTS
                                   H-TRANS.                                   PROJECT NO. 03-7338-004

ENGINE  NO.1                                 TEST NO.1      RUN6
ENGINE  MODEL     0 IHC DT466B               DATE  3/12/84
ENGINE  7.6 L(466. CID) L-6                  TIME                              DIESEL   EM-528-F
CVS NO.  11                                  DYNO NO.  1                       BAG CART NO.  1

BAROMETER 737.36 MM HG(29.03 IN HG)          RELATIVE HUMIDITY ,  ENGINE-51. PCT ,  CVS-50. PCT
DRY BULB TEMP. 23.9 DEG C(75.0 DEG F)        ABSOLUTE HUMIDITY  9.7 GM/KG( 68.2 GRAINS/LB)     NOX HUMIDITY C.F. 1.0000

BAG RESULTS
   BAG NUMBER                                     1                  2                  3                  4
   DESCRIPTION                                   NYNF               LANF               LAF                NYNF
   TIME SECONDS                                  296.0              300.0              305.0              298.0
   TOT. BLOWER RATE SCMM (SCFM)            82.47 ( 2911.9)    82.45 ( 2911.3)    82.46 ( 2911.6)    82.43 ( 2910.8)
   TOT. 20X20 RATE SCMM (SCFM)              9.12 (321.9)       9.12 (321.9)       9.12 (321.9)       9.12 (321.9)
   TOT. 90MM RATE SCMM (SCFM)                .03 (   .99)       .03 (   .99)       .03 (   .99)       .03 (   .99)
   TOT. AUX. SAMPLE RATE SCMM (SCFM)         .05 ( 1.71)        .05 ( 1.71)        .05 ( 1.71)        .05 ( 1.71)
   TOTAL FLOW STD. CU. METRES(SCF)        452.2 (  15967.)   458.2 (16180.)     465.9 (16451.)     455.1 (16069.)

   HC   SAMPLE METER/RANGE/PPM            33.3/21/  17.      37.7/21/  19.      50.0/21/  25.      30.7/21/  15.
   HC   BCKGRD METER/RANGE/PPM            14.8/ 1/   7.      14.8/ 1/   7.      13.5/ 1/   7.      13.0/ 1/   7.
   CO   SAMPLE METER/RANGE/PPM            11.0/13/  10.      16.6/13/  15.      26.3/13/  24.      10.3/13/   9.
   CO   BCKGRD METER/RANGE/PPM              .1/13/   0.        .4/13/   0.        .3/13/   0.        .2/13/   0.
   CO2  SAMPLE METER/RANGE/PCT            75.3/13/  .16      59.0/12/  .24      66.6/11/  .57      75.1/13/  .15
   CO2  BCKGRD METER/RANGE/PCT            21.4/13/  .04      11.7/12/  .04       6.8/11/  .04      21.2/13/  .04
   NOX  SAMPLE METER/RANGE/PPM            53.0/ 1/  16.      78.9/ 1/  23.      67.8/ 2/  68.      52.3/ 1/  16.
   NOX  BCKGRD METER/RANGE/PPM              .6/ 1/   0.        .8/ 1/   0.        .2/ 2/   0.        .9/ 1/   0.

   DILUTION FACTOR                               84.83              55.81              23.26              85.19
   HC   CONCENTRATION PPM                         9.                12.                19.                 9.
   CO   CONCENTRATION PPM                        10.                14.                23.                 9.
   CO2  CONCENTRATION PCT                         .12                .20                .53                .12
   NOX  CONCENTRATION PPM                        15.6               23.2               67.6               15.3

   HC   MASS GRAMS                                2.43               3.06               4.99               2.34
   CO   MASS GRAMS                                5.09               7.69              12.57               4.74
   CO2  MASS GRAMS                              963.8             1659.3             4540.8              969.2
   NOX  MASS GRAMS                               13.48              20.36              60.24              13.31
   FUEL KG (LB)                            .308 (     .68)   .528 (    1.16)   1.438 (    3.17)    .309 (     .68)
   KW HR (HP HR)                           1.00 (    1.34)   1.80 (    2.41)    5.56 (    7.45)   1.00 (    1.34)

   BSHC G/KW HR (G/HP HR)                  2.43 (    1.81)   1.70 (    1.27)    .90 (     .67)    2.34 (    1.75)
   BSCO G/KW HR (G/HP HR)                  5.09 (    3.80)   4.28 (    3.19)   2.26 (    1.69)    4.75 (    3.54)
   BSCO2 G/KW HR (G/HP HR)               964.49 (  719.22) 923.28 (  688.49) 817.37 (  609.51)  969.92 (  723.27)
   BSNOX G/KW HR (G/HP HR)                13.49 (   10.06)  11.33 (    8.45)  10.84 (    8.09)   13.32 (    9.93)
   BSFC KG/KW HR (LB/HP HR)                .308 (    .506)   .294 (    .483)   .259 (    .425)    .309 (    .509)

 TOTAL TEST RESULTS 4 BAGS                                PARTICULATE RESULTS, TOTAL FOR 4 BAGS

   TOTAL KW HR (HP HR)           9.35 ( 12.54)      90MM PARTICULATE RATES     GRAMS/TEST                    9.04
   BSHC  G/KW HR (G/HP HR)       1.37 (  1.02)                                 G/KWHR(G/HPHR)             .97 (  .72)
   BSCO  G/KW HR (G/HP HR)       3.22 (  2.40)                                 G/KG FUEL (G/LB FUEL)     3.50  ( 1.59)
   BSCO2 G/KW HR (G/HP HR)       870. (  649.)                                 FILTER EFF.                  97.9
   BSNOX G/KW HR (G/HP HR)      11.48 (  8.56)
   BSFC  KG/KW HR (LB/HP HR)     .276 (  .454)
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TABLE A-14. INDIVIDUAL HYDROCARBONS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-528-F) DF-2

Individual HC from Test 1, Runs 1-3, 3/12/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	490[a]	52	190
Ethylene	790	84	310
Ethane	12	1.3	5.0
Acetylene	79	8.5	31
Propane	0	0	0
Propylene	320	34	130
Benzene	0	0	0
Toluene	0	0	0

Individual HC from Test 1, Runs 1-3, 3/12/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	85[b]	9.1	34
Ethylene	860	92	340
Ethane	0	0	0
Acetylene	40	4.3	16
Propane	0	0	0
Propylene	420	44	170
Benzene	0	0	0
Toluene	0	0	0

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[a] Methane sample was 2.68 with background of 2.32 ppmC

[b] Methane sample was 2.71 with background of 2.68 ppmC

TABLE A-15. ALDEHYDES FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-528-F) DF-2

Aldehydes from Test 1, Runs 1-3, 3/12/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	510	54	200
Acetaldehyde	360	39	140
Acrolein	190	20	74
Acetone	160	17	63
Propionaldehyde	8.7	0.93	3.5
Crotonaldehyde	0	0	0
Isobutyraldehyde & Methylethylketone	78	8.4	31
Benzaldehyde	0	0	0
Hexanaldehyde	32	3.4	13

Aldehydes from Test 1, Runs 4-6, 3/12/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	630	67	250
Acetaldehyde	550	59	215
Acrolein	170	18	66
Acetone	280	30	110
Propionaldehyde	13	1.4	5.1
Crotonaldehyde	4.9	0.52	1.9
Isobutyraldehyde & Methylethylketone	120	13	48
Benzaldehyde	52	5.5	20
Hexanaldehyde	38	4.1	15

TABLE A-16. PHENOLS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-528-F) DF-2

Phenols from Test 1, Runs 1-3, 3/12/84

Phenol	mg/test	mg/kW-hr	mg/kg fuel
Phenol	0	0	0
Salicylaldehyde	0	0	0
M- & P-cresol	0	0	0
Five[a]	19	2.0	7.4
TNPPH[b]	0	0	0
TR235[c]	0	0	0
T2356[d]	0	0	0

Phenols from Test 1, Runs 4-6, 3/12/84

Sample Voided

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[a] p-ethylphenol, 2-isopropylphenol, 2,3-xylenol, 3,5-xylenol, 2,4,6-trimethylphenol

[b] 2-n-propylphenol

[c] 2,3,5-trimethylphenol

[d] 2,3,5,6-tetramethylphenol

TABLE A-17. SUMMARY OF TIA BY DOAS[a] FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-528-F) DF-2

Test No.	Run No.	LCA µg/ℓ	TIA[b]	LCO µg/ℓ	TIA[c]
1	1-3	6.78	0.98	1.23	1.09
1	4-6	7.45	1.01	2.73	1.44

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[a] These measurements were based on DOAS standard corresponding for use of No. 2 diesel fuel. Samples were taken from dilute exhaust of approximately 12:1 for the overall transient cycle.

[b] TIA based on liquid column aromatics (LCA) by:
$\text{TIA} = 0.4 + 0.7 \log_{10} (\text{LCA})$

[c] TIA based on liquid column oxygenates (LCO) by:
$\text{TIA} = 1 + \log_{10} (\text{LCO})$, (TIA by LCO perferred)

TABLE A-18. FEDERAL SMOKE TEST TRACE EVALUATION

Engine Model: IH DT-466B Test No. 1 Date: 3/13/84
Engine S/N: Fuel: EM-528-F Run No. 1 Eval. By: Kathy Jack

Accelerations Observed Power: 199.5hp Barometer: 29.32 in. Hg.

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	12.0	1	11.5	1	11.0
2	11.3	2	12.0	2	11.5
3	11.5	3	12.3	3	17.0
4	14.0	4	12.0	4	15.0
5	21.0	5	12.0	5	13.4
6	15.0	6	12.3	6	13.5
7	14.3	7	19.0	7	11.5
8	11.4	8	15.0	8	12.0
9	11.0	9	11.0	9	12.0
10	11.3	10	13.0	10	11.5
11	11.0	11	12.8	11	11.4
12	10.4	12	11.4	12	11.0
13	11.5	13	11.0	13	11.5
14	11.5	14	10.5	14	12.3
15	11.4	15	11.0	15	12.5

Total Smoke % 188.6 186.8 187.1

Factor (a) = $\frac{562.5}{45}$ = 12.5 % -1 FOR OVERALL DRIFT 11.5%

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	10.0	1	8.4	1	10.8
2	11.0	2	8.5	2	10.6
3	9.9	3	8.5	3	10.4
4	9.9	4	8.4	4	10.5
5	9.7	5	8.3	5	9.9

Total Smoke % 50.5 42.1 52.2

Factor (b) = $\frac{144.8}{15}$ = 9.7 % -1 FOR OVERALL DRIFT 8.7%

Peak

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	21.0	1	19.0	1	17.0
2	15.0	2	15.0	2	15.0
3	14.3	3	13.0	3	13.5

Total Smoke % 50.3 47.0 45.5

Factor (c) = $\frac{142.8}{9}$ = 15.9 % -1 FOR OVERALL DRIFT 14.9%

APPENDIX B

RESULTS FROM OPERATION ON EM-586-F, GEOKINETICS

TABLE B-1

7-MODE DIESEL EMISSION CYCLE

ENGINE: IH DT466B SHALE OIL : GEOKINETICS BAROMETER: 29.15
TEST-02-01 FUEL: EM-586-F PROJECT: 03-7338-004 DATE: 2/15/84

MODE	POWER PCT	ENGINE SPEED COND / RPM	TORQUE OBS LB-FT	POWER OBS BHP	FUEL FLOW LB/MIN	AIR FLOW LB/MIN	INTAKE HUMID GR/LB	NOX CORR FACT	MEASURED HC PPM	MEASURED CO PPM	MEASURED CO2 PCT	MEASURED NOX PPM	CALCULATED GRAMS / HOUR HC	CALCULATED GRAMS / HOUR CO	CALCULATED GRAMS / HOUR NOX	MODE
1	2	INTER / 1800.	9.	3.0	.145	14.91	60.	.929	370.	628.	2.00	275.	71.	241.	160.	1
2	50	INTER / 1800.	224.	76.8	.495	17.02	29.	.887	235.	267.	6.37	840.	52.	114.	521.	2
3	100	INTER / 1800.	434.	148.8	.945	21.49	77.	1.003	220.	1002.	9.53	1200.	64.	545.	1069.	3
4		IDLE / 700.	0.	.0	.040	5.73	76.	.959	500.	769.	1.35	245.	37.	116.	58.	4
5	100	RATED / 2600.	427.	211.5	1.428	37.49	60.	.965	200.	1016.	8.68	1200.	95.	917.	1705.	5
6	50	RATED / 2600.	217.	107.5	.790	28.35	76.	.985	245.	244.	6.28	740.	88.	169.	826.	6
7	2	RATED / 2600.	9.	4.3	.280	21.94	77.	.988	375.	453.	2.84	255.	100.	241.	219.	7

MODE	CALCULATED GRAMS/LB-FUEL HC	CALCULATED GRAMS/LB-FUEL CO	CALCULATED GRAMS/LB-FUEL NOX	CALCULATED GRAMS/BHP-HR HC	CALCULATED GRAMS/BHP-HR CO	CALCULATED GRAMS/BHP-HR NOX	F/A DRY MEAS	F/A STOICH	"PHI"	WET HC CORR FACT	F/A CALC	F/A PCT MEAS	POWER CORR FACT	BSFC CORR LB/HP-HR	MODAL WEIGHT FACTOR	MODE
1	8.15	27.71	18.40	23.64	80.35	53.35	.0098	.0698	.140	.980	.0099	.5	1.015	2.856	.120	1
2	1.75	3.85	17.55	.68	1.49	6.79	.0292	.0698	.418	.948	.0296	1.3	1.018	.380	.160	2
3	1.12	9.62	18.86	.43	3.67	7.19	.0445	.0698	.637	.922	.0439	-1.2	1.030	.370	.120	3
4	15.58	48.23	24.04	************		******	.0071	.0698	.101	.985	.0070	-1.5	1.012	*****	.200	4
5	1.11	10.70	19.89	.45	4.33	8.06	.0384	.0698	.550	.929	.0402	4.6	1.072	.378	.120	5
6	1.86	3.57	17.42	.82	1.58	7.68	.0282	.0698	.403	.946	.0292	3.6	1.049	.420	.160	6
7	5.98	14.36	13.04	23.19	55.67	50.54	.0129	.0698	.185	.973	.0137	6.0	1.029	3.767	.120	7

CYCLE COMPOSITE USING 7-MODE WEIGHT FACTORS

BSHC ------- = .944 GRAM/BHP-HR
BSCO ------- = 4.102 GRAM/BHP-HR
BSNOX ------ = 8.227 GRAM/BHP-HR
BSHC + BSNOX = 9.171 GRAM/BHP-HR
CORR. BSFC - = .428 LBS/BHP-HR

TABLE B-2. SUPPLEMENTARY ENGINE DATA OBTAINED OVER 7-MODE TESTING ON (EM-586-F) GEOKINETICS CRUDE SHALE OIL

Test Mode No.	Fuel			Inlet Air			Exhaust		Oil	
	Temp.[a] °F	Press.[b] psi	Injector Temp.[c] °F	Temp. °F	Restrict. in. H_2O	Boost psi	Temp. °F	B.P. in. Hg	Temp. °F	Press. psi
1	195	42	226	91.5	5.4	0.7	385	0.2	d	49
2	220	36.0	216	91	6.6	3.2	732	0.3	d	47
3	195	60	217	91	9.9	9.5	1034	0.6	d	44.5
4	211	35.5	216	95	1.2	0.1	344	0.05	d	19.5
5	187	50	226	90	26.5	17.8	1084	2.1	d	48
6	207	60	222	93	16.1	7.5	802	0.95	d	51
7	196	60	220	90	10.1	1.6	482	0.4	d	52

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[a] Measured at fuel inlet to pump

[b] Measured after secondary filter

[c] Measured approximately 2 inches upstream of injector No. 1

[d] No data

TABLE B-3

13-MODE FEDERAL DIESEL EMISSION CYCLE 1979

ENGINE: IHC 466T SHALE OIL: GEOKINETICS H/C 1.69 BAROMETER: 28.69
TEST-03-01 FUEL: EM-586-F PROJECT: 03-7338-004 DATE: 3/26/84

MODE	POWER PCT	ENGINE SPEED COND / RPM	TORQUE OBS LB-FT	POWER OBS BHP	FUEL FLOW LB/MIN	AIR FLOW LB/MIN	INTAKE HUMID GR/LB	NOX CORR FACT	MEASURED HC PPM	MEASURED CO PPM	MEASURED CO2 PCT	MEASURED NOX PPM	CALCULATED GRAMS / HOUR HC	CALCULATED GRAMS / HOUR CO	CALCULATED GRAMS / HOUR NOX	MODE
1		IDLE / 609.	0.	.0	.033	4.73	52.	.918	335.	769.	1.52	320.	19.	87.	54.	1
2	2	INTER / 1800.	8.	2.7	.167	14.95	52.	.933	368.	629.	2.14	245.	76.	260.	154.	2
3	25	INTER / 1800.	100.	34.3	.285	15.47	52.	.939	300.	493.	4.04	480.	59.	189.	283.	3
4	50	INTER / 1800.	201.	68.9	.447	16.70	52.	.943	253.	304.	6.27	770.	51.	119.	465.	4
5	75	INTER / 1800.	301.	103.2	.733	19.08	52.	.955	210.	158.	7.79	1050.	57.	82.	852.	5
6	100	INTER / 1800.	398.	136.4	1.000	21.65	52.	.961	210.	517.	9.21	1138.	67.	309.	1068.	6
7		IDLE / 610.	0.	.0	.033	4.73	52.	.911	255.	604.	1.43	310.	15.	74.	56.	7
8	100	RATED / 2600.	396.	196.0	1.428	35.80	49.	.948	180.	692.	8.48	1075.	88.	641.	1541.	8
9	75	RATED / 2600.	302.	149.5	1.140	32.21	49.	.943	160.	327.	7.32	900.	72.	281.	1190.	9
10	50	RATED / 2600.	200.	99.0	.767	28.25	49.	.934	160.	213.	5.94	660.	59.	152.	717.	10
11	25	RATED / 2600.	100.	49.5	.510	24.38	49.	.927	165.	327.	4.45	440.	53.	206.	419.	11
12	2	RATED / 2600.	8.	4.0	.303	22.35	55.	.940	275.	517.	2.83	230.	80.	299.	204.	12
13		IDLE / 600.	0.	.0	.033	4.64	55.	.927	440.	1007.	1.43	205.	26.	118.	36.	13

MODE	CALCULATED GRAMS/LB-FUEL HC	CALCULATED GRAMS/LB-FUEL CO	CALCULATED GRAMS/LB-FUEL NOX	CALCULATED GRAMS/BHP-HR HC	CALCULATED GRAMS/BHP-HR CO	CALCULATED GRAMS/BHP-HR NOX	F/A DRY MEAS	F/A STOICH	"PHI"	WET HC CORR FACT	F/A CALC	F/A PCT MEAS	POWER CORR FACT	BSFC CORR LB/HP-HR	MODAL WEIGHT FACTOR	MODE
1	9.47	43.66	27.22	************		******	.0071	.0698	.102	.984	.0077	8.2	1.016	*****	.067	1
2	7.61	26.00	15.42	27.74	94.82	56.22	.0112	.0698	.161	.980	.0105	-6.3	1.024	3.563	.080	2
3	3.42	11.08	16.52	1.71	5.53	8.24	.0186	.0698	.266	.964	.0192	3.4	1.025	.487	.080	3
4	1.92	4.45	17.35	.75	1.73	6.75	.0269	.0698	.386	.947	.0292	8.4	1.028	.378	.080	4
5	1.30	1.87	19.35	.55	.80	8.25	.0387	.0698	.555	.936	.0359	-7.3	1.030	.414	.080	5
6	1.11	5.16	17.80	.49	2.27	7.83	.0465	.0698	.667	.925	.0423	-9.0	1.036	.425	.080	6
7	7.74	36.89	28.14	************		******	.0071	.0698	.102	.985	.0071	.6	1.019	*****	.067	7
8	1.02	7.48	17.98	.45	3.27	7.86	.0402	.0698	.576	.931	.0392	-2.5	1.084	.403	.080	8
9	1.05	4.11	17.40	.48	1.88	7.96	.0356	.0698	.511	.940	.0339	-5.0	1.069	.428	.080	9
10	1.28	3.30	15.59	.59	1.53	7.24	.0273	.0698	.392	.950	.0276	1.0	1.056	.440	.080	10
11	1.73	6.73	13.70	1.07	4.16	8.47	.0211	.0698	.302	.961	.0209	-.7	1.046	.591	.080	11
12	4.40	16.45	11.23	20.23	75.61	51.61	.0137	.0698	.196	.974	.0136	-.4	1.039	4.422	.080	12
13	12.86	59.20	18.24	************		******	.0072	.0698	.104	.985	.0074	2.5	1.016	*****	.067	13

CYCLE COMPOSITE USING 13-MODE WEIGHT FACTORS

BSHC ------- = .843 GRAM/BHP-HR
BSCO ------- = 3.288 GRAM/BHP-HR
BSNOX ------ = 8.318 GRAM/BHP-HR
BSHC + BSNOX = 9.161 GRAM/BHP-HR
CORR. BSFC - = .463 LBS/BHP-HR

TABLE B-4. SUPPLEMENTARY ENGINE DATA OBTAINED OVER 13-MODE TESTING ON (EM-586-F) GEOKINETICS CRUDE SHALE OIL

Test	Fuel			Inlet Air			Exhaust		Oil	
Mode No.	Temp.[a] °F	Press.[b] psi	Injector Temp.[c] ° F	Temp. ° F	Restrict. in. H_2O	Boost psi	Temp. °F	B.P. in. Hg	Temp. °F	Press. psi
1	191	31.0	222	87	1.0	0	342	0	196	d
2	173	44.5	226	84	5.5	0.6	355	0.15	198	d
3	169	44.5	228	84	5.8	1.3	498	0.2	201	d
4	179	44.0	231	85	6.7	3.1	686	0.3	207	d
5	194	42.0	230	84	7.9	5.2	829	0.4	210	d
6	206	42.0	223	84	9.9	8.7	981	0.6	214	d
7	224	30.0	222	89	1.0	0	431	0	200	d
8	182	44.5	225	87	25.3	15.7	1054	2.4	219	d
9	210	52.0	222	87	20.2	11.6	947	1.7	229	d
10	213	52.0	—	86	16.1	7.4	827	1.2	227	d
11	210	57.0	—	86	12.5	3.9	674	0.8	223	d
12	202	51.0	—	85	10.5	1.8	513	0.55	216	d
13	192	30.0	—	87	1.0	0	321	0	202	d

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[a] Measured at fuel inlet to pump
[b] Measured after secondary filter
[c] Measured approximately 2 inches upstream of injector No. 1
[d] No Data

TABLE B-5. REGULATED EMISSIONS SUMMARY FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-586-F) GEOKINETICS

Test No.	Run No.	Transient Emissions, g/kW-hr (g/hp-hr)				Cycle BSFC kg/kW-hr (lb/hp-hr)	Cycle Work[a] kW-hr (hp-hr)
		HC	CO	NO_x	Part.		
3	1	2.20 (1.64)	4.53 (3.38)	10.53 (7.85)	2.16 (1.61)	0.275 (0.452)	9.24 (12.39)
3	2	2.16 (1.61)	4.47 (3.33)	10.62 (7.92)	2.01 (1.50)	0.273 (0.449)	9.24 (12.39)

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[a] All runs met statisticla criteria

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                         TABLE B-6. ENGINE EMISSION RESULTS
                                    H-TRANS.                                         PROJECT NO. 03-7338-004

ENGINE  NO.1                                 TEST NO.3      RUN1
ENGINE  MODEL     0 IHC DT466B               DATE  3/23/84
ENGINE  7.6 L(466. CID) L-6                  TIME                                DIESEL   EM-586-F
CVS NO.  11                                  DYNO NO.  1                         BAG CART NO.  1

BAROMETER 735.33 MM HG(28.95 IN HG)          RELATIVE HUMIDITY ,  ENGINE-58. PCT ,  CVS-47. PCT
DRY BULB TEMP. 24.4 DEG C(76.0 DEG F)        ABSOLUTE HUMIDITY 11.5 GM/KG( 80.7 GRAINS/LB)      NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                         1                   2                   3                   4
  DESCRIPTION                                      NYNF                LANF                 LAF                NYNF
  TIME SECONDS                                     296.0               300.0               305.0               298.0
  TOT. BLOWER RATE SCMM (SCFM)               82.08 ( 2898.2)     82.07 ( 2897.9)     82.08 ( 2898.2)     82.04 ( 2896.7)
  TOT. 20X20 RATE SCMM (SCFM)                8.62 (304.3)        8.62 (304.3)        8.62 (304.3)        8.62 (304.3)
  TOT. 90MM RATE SCMM (SCFM)                  .02 (  .58)         .02 (  .58)         .02 (  .58)         .02 (  .58)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)           .03 ( 1.22)         .03 ( 1.22)         .03 ( 1.22)         .03 ( 1.22)
  TOTAL FLOW STD. CU. METRES(SCF)            447.7 (  15808.)    453.7 (16020.)      461.3 (16289.)      450.5 (15907.)

  HC   SAMPLE METER/RANGE/PPM                30.2/22/  30.       22.5/22/  22.       29.8/22/  30.       22.7/22/  23.
  HC   BCKGRD METER/RANGE/PPM                 6.7/ 2/   7.        7.0/ 2/   7.        7.0/ 2/   7.        7.3/ 2/   7.
  CO   SAMPLE METER/RANGE/PPM                24.2/13/  22.       23.3/13/  21.       27.3/13/  25.       18.2/13/  17.
  CO   BCKGRD METER/RANGE/PPM                 1.0/13/   1.        1.3/13/   1.        1.2/13/   1.        1.1/13/   1.
  CO2  SAMPLE METER/RANGE/PCT                74.5/13/  .15       59.6/12/  .24       65.4/11/  .55       73.7/13/  .15
  CO2  BCKGRD METER/RANGE/PCT                22.8/13/  .04       12.3/12/  .04        7.1/11/  .04       22.8/13/  .04
  NOX  SAMPLE METER/RANGE/PPM                46.1/ 1/  14.       75.9/ 1/  23.       62.4/ 2/  62.       48.7/ 1/  14.
  NOX  BCKGRD METER/RANGE/PPM                 1.3/ 1/   0.        1.3/ 1/   0.         .6/ 2/   1.        1.8/ 1/   1.

  DILUTION FACTOR                                84.49               54.93               24.15               86.22
  HC   CONCENTRATION PPM                         24.                 16.                 23.                 15.
  CO   CONCENTRATION PPM                         21.                 20.                 23.                 15.
  CO2  CONCENTRATION PCT                          .11                 .20                 .51                 .11
  NOX  CONCENTRATION PPM                         13.3                22.2                61.8                14.0

  HC   MASS GRAMS                                 6.08                4.08                6.14                4.03
  CO   MASS GRAMS                                10.86               10.41               12.54                8.01
  CO2  MASS GRAMS                               916.1              1649.6              4310.6               906.1
  NOX  MASS GRAMS                                11.41               19.26               54.54               12.03
  FUEL KG (LB)                               .305 (    .67)      .539 (   1.19)     1.395 (   3.08)      .299 (    .66)
  KW HR (HP HR)                               .99 (   1.33)      1.78 (   2.39)      5.47 (   7.34)       .99 (   1.33)

  BSHC G/KW HR (G/HP HR)                     6.13 (   4.57)      2.29 (   1.71)      1.12 (    .84)      4.06 (   3.03)
  BSCO G/KW HR (G/HP HR)                    10.95 (   8.16)      5.84 (   4.36)      2.29 (   1.71)      8.08 (   6.02)
  BSCO2 G/KW HR (G/HP HR)                  923.65 ( 688.76)    925.57 ( 690.20)    787.55 ( 587.28)    913.59 ( 681.27)
  BSNOX G/KW HR (G/HP HR)                   11.51 (   8.58)     10.81 (   8.06)      9.96 (   7.43)     12.13 (   9.04)
  BSFC KG/KW HR (LB/HP HR)                   .308 (   .506)      .302 (   .497)      .255 (   .419)      .301 (   .495)

TOTAL TEST RESULTS 4 BAGS                             PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)           9.24 ( 12.39)         90MM PARTICULATE RATES    GRAMS/TEST                 19.98
  BSHC   G/KW HR (G/HP HR)      2.20 (  1.64)                                   G/KWHR(G/HPHR)             2.16  ( 1.61)
  BSCO   G/KW HR (G/HP HR)      4.53 (  3.38)                                   G/KG FUEL (G/LB FUEL)      7.87  ( 3.57)
  BSCO2 G/KW HR (G/HP HR)       842. (  628.)                                   FILTER EFF.                93.9
  BSNOX G/KW HR (G/HP HR)      10.53 (  7.85)
  BSFC   KG/KW HR (LB/HP HR)    .275 (  .452)
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                                           TABLE B-7. ENGINE EMISSION RESULTS
                                                       H-TRANS.                                    PROJECT NO. 03-7338-004
ENGINE  NO.
ENGINE  MODEL     0 IHC DT466B                       TEST NO.3       RUN2
ENGINE  7.6 L(466. CID) L-6                          DATE  3/23/84
CVS NO.  11                                          TIME                                DIESEL   EM-586-F
                                                     DYNO NO.  1                         BAG CART NO.  1

BAROMETER 735.08 MM HG(28.94 IN HG)                  RELATIVE HUMIDITY ,  ENGINE-58. PCT ,  CVS-47. PCT
DRY BULB TEMP. 24.4 DEG C(76.0 DEG F)                ABSOLUTE HUMIDITY 11.5 GM/KG( 80.7 GRAINS/LB)       NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                        1                    2                    3                    4
  DESCRIPTION                                      NYNF                 LANF                 LAF                  NYNF
  TIME SECONDS                                     296.0                300.0                305.0                298.0
  TOT. BLOWER RATE SCMM (SCFM)               82.35 ( 2907.8)      82.35 ( 2907.9)      81.97 ( 2894.4)      82.33 ( 2907.0)
  TOT. 20X20 RATE SCMM (SCFM)                 8.57 (302.6)         8.57 (302.6)         8.57 (302.6)         8.57 (302.6)
  TOT. 90MM RATE SCMM (SCFM)                   .02 (   .59)         .02 (   .59)         .02 (   .59)         .02 (   .59)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)            .03 ( 1.22)          .03 ( 1.22)          .03 ( 1.22)          .03 ( 1.22)
  TOTAL FLOW STD. CU. METRES(SCF)            448.8 (  15847.)     454.9 (16061.)       460.5 (16261.)       451.7 (15950.)

  HC   SAMPLE METER/RANGE/PPM                27.0/22/  27.        23.1/22/  23.        30.8/22/  31.        22.7/22/  23.
  HC   BCKGRD METER/RANGE/PPM                 7.0/ 2/   7.         7.0/ 2/   7.         7.0/ 2/   7.         7.0/ 2/   7.
  CO   SAMPLE METER/RANGE/PPM                22.8/13/  21.        23.3/13/  21.        27.2/13/  25.        18.1/13/  16.
  CO   BCKGRD METER/RANGE/PPM                  .5/13/   0.         1.3/13/   1.         1.4/13/   1.         1.1/13/   1.
  CO2  SAMPLE METER/RANGE/PCT                74.0/13/  .15        58.1/12/  .23        65.6/11/  .55        74.1/13/  .15
  CO2  BCKGRD METER/RANGE/PCT                22.6/13/  .04        12.6/12/  .04         7.3/11/  .04        22.1/13/  .04
  NOX  SAMPLE METER/RANGE/PPM                47.9/ 1/  14.        73.8/ 1/  22.        63.1/ 2/  63.        49.5/ 1/  15.
  NOX  BCKGRD METER/RANGE/PPM                 1.4/ 1/   0.         1.4/ 1/   0.          .6/ 2/   1.         1.5/ 1/   0.

  DILUTION FACTOR                              85.37                56.58                24.04                85.71
  HC   CONCENTRATION PPM                       20.                  16.                  24.                  16.
  CO   CONCENTRATION PPM                       20.                  20.                  23.                  15.
  CO2  CONCENTRATION PCT                        .11                  .19                  .51                  .11
  NOX  CONCENTRATION PPM                       13.8                 21.5                 62.5                 14.3

  HC   MASS GRAMS                               5.18                 4.26                 6.39                 4.11
  CO   MASS GRAMS                              10.44                10.44                12.38                 7.99
  CO2  MASS GRAMS                              911.7               1585.0               4313.3                927.7
  NOX  MASS GRAMS                              11.88                18.74                55.06                12.34
  FUEL KG (LB)                               .303 (     .67)      .518 (    1.14)     1.396 (    3.08)      .306 (     .67)
  KW HR (HP HR)                               .99 (    1.33)      1.78 (    2.39)      5.47 (    7.33)       .99 (    1.33)

  BSHC G/KW HR (G/HP HR)                     5.23 (    3.90)      2.39 (    1.78)      1.17 (     .87)      4.15 (    3.09)
  BSCO G/KW HR (G/HP HR)                    10.53 (    7.85)      5.86 (    4.37)      2.27 (    1.69)      8.05 (    6.00)
  BSCO2 G/KW HR (G/HP HR)                  919.29 (  685.52)    889.32 (  663.17)    789.12 (  588.45)    935.42 (  697.54)
  BSNOX G/KW HR (G/HP HR)                   11.98 (    8.93)     10.52 (    7.84)     10.07 (    7.51)     12.44 (    9.28)
  BSFC KG/KW HR (LB/HP HR)                   .305 (    .502)      .291 (    .478)      .255 (    .420)      .308 (    .507)

TOTAL TEST RESULTS 4 BAGS                                      PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)          9.23 ( 12.38)                   90MM PARTICULATE RATES     GRAMS/TEST                   18.54
  BSHC   G/KW HR (G/HP HR)     2.16 (  1.61)                                              G/KWHR(G/HPHR)            2.01  ( 1.50)
  BSCO   G/KW HR (G/HP HR)     4.47 (  3.33)                                              G/KG FUEL (G/LB FUEL)     7.35  ( 3.33)
  BSCO2 G/KW HR (G/HP HR)      838. (  625.)                                              FILTER EFF.                  97.1
  BSNOX G/KW HR (G/HP HR)     10.62 (  7.92)
  BSFC   KG/KW HR (LB/HP HR)   .273 (  .449)
```

TABLE B-8. INDIVIDUAL HYDROCARBONS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-586-F) GEOKINETICS CRUDE SHALE OIL

Individual HC from Test 3, Run 1, 3/23/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	130	14	51
Ethylene	1300	140	500
Ethane	13	1.4	5.0
Acetylene	49	5.3	19
Propane	0	0	0
Propylene	500	54	200
Benzene	0	0	0
Toluene	0	0	0

Individual HC from Test 3, Run 2, 3/23/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	100	11	41
Ethylene	1200	130	480
Ethane	12	1.3	4.9
Acetylene	49	5.3	19
Propane	0	0	0
Propylene	520	56	200
Benzene	0	0	0
Toluene	0	0	0

TABLE B-9. ALDEHYDES FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-586-F) GEOKINETICS CRUDE SHALE OIL

Aldehydes from Test 3, Run 1, 3/23/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1100	120	430
Acetaldehyde	930	100	370
Acrolein	390	42	150
Acetone	560	61	220
Propionaldehyde	0	0	0
Crotonaldehyde	200	22	79
Isobutyraldehyde & Methylethylketone	170	18	66
Benzaldehyde	120	13	47
Hexanaldehyde	130	15	53

Aldehydes from Test 3, Run 2, 3/23/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1100	120	450
Acetaldehyde	950	100	380
Acrolein	450	49	180
Acetone	440	48	170
Propionaldehyde	250	27	100
Crotonaldehyde	130	14	51
Isobutyraldehyde & Methylethylketone	78	8.4	31
Benzaldehyde	120	13	48
Hexanaldehyde	140	15	54

TABLE B-10. PHENOLS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-586-F) GEOKINETICS CRUDE SHALE OIL

Phenols from Test 3, Run 1, 3/23/84

Phenol	mg/test	mg/kW-hr	mg/kg fuel
Phenol	0	0	0
Salicylaldehyde	0	0	0
M- & P-cresol	0	0	0
Five[a]	190	20	75
TNPPH[b]	0	0	0
TR235[c]	54	5.8	21
T2356[d]	0	0	0

Phenols from Test 3, Run 2, 3/23/84

No Phenols above background levels detected

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[a] p-ethylphenol, 2-isopropylphenol, 2,3-xylenol, 3,5-xylenol, 2,4,6-trimethylphenol

[b] 2-n-propylphenol

[c] 2,3,5-trimethylphenol

[d] 2,3,5,6-tetramethylphenol

TABLE B-11. SUMMARY OF TIA BY DOAS[a] FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-586-F) GEOKINETICS CRUDE SHALE OILS

Test No.	Run No.	LCA µg/ℓ	TIA[b]	LCO µg/ℓ	TIA[c]
3	1	22.71	1.35	19.99	2.30
3	2	21.20	1.33	21.63	2.34

---

[a] These measurements were based on DOAS standard corresponding for use of No. 2 diesel fuel. Samples were taken from dilute exhaust of approximately 12:1 for the overall transient cycle.

[b] TIA based on liquid column aromatics (LCA) by:
$TIA = 0.4 + 0.7 \log_{10} (LCA)$

[c] TIA based on liquid column oxygenates (LCO) by:
$TIA = 1 + \log_{10} (LCO)$, (TIA by LCO perferred)

EM-55C-F

TABLE B-12. FEDERAL SMOKE TEST TRACE EVALUATION

Engine Model: IH DT-466B Test No. 3 Date: 3/23/84
Engine S/N: Fuel: EM-586-F Run No. 1 Eval. By: K. Jack
Observed Power: 195 hp Barometer: 28.91 in. Hg

Accelerations

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	37.0	1	40.0	1	36.0
2	20.0	2	60.0	2	70.0
3	13.8	3	43.0	3	42.5
4	12.0	4	26.0	4	29.0
5	9.8	5	21.5	5	20.0
6	11.5	6	21.5	6	22.5
7	14.5	7	26.5	7	22.0
8	20.0	8	25.0	8	25.0
9	12.5	9	17.0	9	19.0
10	9.8	10	12.0	10	20.3
11	11.2	11	15.0	11	22.0
12	13.0	12	13.0	12	12.0
13	10.0	13	10.5	13	10.5
14	9.8	14	10.2	14	10.5
15	9.8	15	10.0	15	11.3
Total Smoke %	214.7		351.2		372.1

Factor (a) = $\frac{938.5}{45}$ = 20.9 %

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	7.0	1	6.8	1	6.0
2	6.7	2	5.5	2	7.2
3	6.6	3	5.8	3	6.0
4	7.5	4	5.3	4	5.5
5	7.3	5	6.0	5	5.5
Total Smoke %	35.1		29.4		30.2

Factor (b) = $\frac{94.7}{15}$ = 6.3 %

Peak

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	37.0	1	60.0	1	70.0
2	20.0	2	43.0	2	42.5
3	20.0	3	40.0	3	36.0
Total Smoke %	77.0		143.0		148.5

Factor (c) = $\frac{220.0}{9}$ = 24.4 %

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APPENDIX C

RESULTS FROM OPERATION ON EM-584-F, SUPERIOR

TABLE C-1

7-MODE DIESEL EMISSION CYCLE

ENGINE: IH DT466B SHALE OIL : SUPERIOR BAROMETER: 29.10
[illegible]-03-01 FUEL: EM-584-F PROJECT: 03-7338-004 DATE: 2/22/84

MODE	POWER PCT	ENGINE SPEED COND / RPM	TORQUE OBS LB-FT	POWER OBS BHP	FUEL FLOW LB/MIN	AIR FLOW LB/MIN	INTAKE HUMID GR/LB	NOX CORR FACT	MEASURED HC PPM	MEASURED CO PPM	MEASURED CO2 PCT	MEASURED NOX PPM	CALCULATED GRAMS / HOUR HC	CALCULATED GRAMS / HOUR CO	CALCULATED GRAMS / HOUR NOX	MODE
1	2	INTER / 1800.	11.	3.6	.162	14.93	26.	.845	900.	1257.	2.15	285.	170.	481.	150.	1
2	50	INTER / 1800.	222.	76.2	.495	17.04	26.	.884	240.	388.	6.71	885.	50.	159.	522.	2
3	100	INTER / 1800.	420.	144.0	.945	20.74	26.	.919	280.	1043.	9.64	1260.	79.	565.	1024.	3
4		IDLE / 700.	0.	.0	.040	5.72	24.	.818	1000.	1302.	1.35	195.	70.	184.	37.	4
5	100	RATED / 2600.	392.	194.1	1.428	34.96	23.	.902	235.	1016.	8.48	1020.	113.	945.	1396.	5
6	50	RATED / 2600.	215.	106.6	.790	27.20	24.	.876	300.	310.	6.62	740.	102.	205.	701.	6
7	2	RATED / 2600.	7.	3.5	.297	22.00	26.	.845	850.	832.	2.95	330.	225.	443.	242.	7

MODE	CALCULATED GRAMS/LB-FUEL HC	CALCULATED GRAMS/LB-FUEL CO	CALCULATED GRAMS/LB-FUEL NOX	CALCULATED GRAMS/BHP-HR HC	CALCULATED GRAMS/BHP-HR CO	CALCULATED GRAMS/BHP-HR NOX	F/A DRY MEAS	F/A STOICH	"PHI"	WET HC CORR FACT	F/A CALC	F/A PCT MEAS	POWER CORR FACT	BSFC CORR LB/HP-HR	MODAL WEIGHT FACTOR	MODE
1	17.57	49.57	15.50	47.34	133.57	41.76	.0109	.0706	.154	.981	.0110	1.6	1.017	2.651	.120	1
2	1.69	5.35	17.59	.66	2.08	6.86	.0292	.0706	.413	.948	.0310	6.3	1.019	.383	.160	2
3	1.40	9.96	18.05	.55	3.92	7.11	.0457	.0706	.648	.928	.0442	-3.2	1.027	.383	.120	3
4	29.04	76.86	15.37	******	******	******	.0070	.0706	.099	.988	.0074	5.5	1.013	*****	.200	4
5	1.32	11.02	16.29	.58	4.87	7.19	.0410	.0706	.581	.936	.0391	-4.5	1.073	.412	.120	5
6	2.15	4.33	14.78	.95	1.93	6.57	.0291	.0706	.413	.949	.0306	5.0	1.033	.431	.160	6
7	12.67	24.89	13.61	65.04	127.82	69.90	.0135	.0706	.192	.976	.0145	7.1	1.030	4.986	.120	7

CYCLE COMPOSITE USING 7-MODE WEIGHT FACTORS

BSHC ------- = 1.541 GRAM/BHP-HR
BSCO ------- = 5.478 GRAM/BHP-HR
BSNOX ------ = 7.649 GRAM/BHP-HR
BSHC + BSNOX = 9.190 GRAM/BHP-HR
CORR. BSFC - = .451 LBS/BHP-HR

TABLE C-2. SUPPLEMENTARY ENGINE DATA OBTAINED OVER 7-MODE TESTING ON (EM-584-F) SUPERIOR CRUDE SHALE OIL

Test	Fuel			Inlet Air			Exhaust		Oil	
Mode No.	Temp.[a] ° F	Press.[b] psi	Injector Temp.[c] ° F	Temp. ° F	Restrict. in. H_2O	Boost psi	Temp. ° F	B.P. in. Hg	Temp. ° F	Press. psi
1	263	60	299	90	5.3	0.7	448	0.6	d	d
2	260	60	305	89	6.7	3.3	764	1.0	d	d
3	254	60	300	90	9.2	8.2	933	1.7	d	d
4	244	59	290	95	1.2	0	345	0.1	d	d
5	276	70	297	92	24.5	16.0	1081	2.6	d	d
6	265	70	292	92	15.4	6.8	849	2.8	d	d
7	280	60	315	92	10.3	1.8	548	1.35	d	d

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[a] Measured at fuel inlet to pump

[b] Measured after secondary filter

[c] Measured approximately 2 inches upstream of injector No. 1

[d] No data

TABLE C-3

13-MODE FEDERAL DIESEL EMISSION CYCLE 1979

ENGINE: IHC DT466B SHALE OIL: SUPERIOR H/C RATIO 1.58 BAROMETER 29.28
TEST-02-01 FUEL: EM-584-F PROJECT: 03-7338-004 DATE: 3/20/84

MODE	POWER PCT	ENGINE SPEED COND / RPM	TORQUE OBS LB-FT	POWER OBS BHP	FUEL FLOW LB/MIN	AIR FLOW LB/MIN	INTAKE HUMID GR/LB	NOX CORR FACT	MEASURED HC PPM	MEASURED CO PPM	MEASURED CO2 PCT	MEASURED NOX PPM	CALCULATED GRAMS / HOUR HC	CALCULATED GRAMS / HOUR CO	CALCULATED GRAMS / HOUR NOX	MODE
1		IDLE / 630.	0.	.0	.050	5.13	57.	.975	438.	1411.	1.34	210.	40.	259.	61.	1
2	2	INTER / 1800.	9.	3.1	.153	15.42	57.	.983	610.	1199.	2.19	280.	110.	434.	163.	2
3	25	INTER / 1800.	101.	34.6	.292	15.87	34.	.918	320.	692.	4.17	560.	62.	265.	321.	3
4	50	INTER / 1800.	200.	68.5	.455	17.21	43.	.937	238.	409.	5.94	770.	51.	174.	500.	4
5	75	INTER / 1800.	301.	103.2	.600	19.41	43.	.939	215.	373.	6.70	975.	55.	185.	743.	5
6	100	INTER / 1800.	396.	135.7	.815	21.57	40.	.937	220.	718.	9.10	1075.	57.	356.	816.	6
7		IDLE / 626.	0.	.0	.050	5.02	40.	.906	440.	1255.	1.34	215.	40.	233.	59.	7
8	100	RATED / 2600.	378.	187.1	1.290	36.64	39.	.931	185.	730.	8.18	975.	84.	638.	1293.	8
9	75	RATED / 2600.	300.	148.5	1.068	32.99	38.	.927	180.	481.	7.14	838.	77.	399.	1052.	9
10	50	RATED / 2600.	200.	99.0	.780	29.15	38.	.924	158.	373.	5.94	640.	59.	272.	704.	10
11	25	RATED / 2600.	101.	50.0	.510	25.46	40.	.923	175.	579.	4.45	470.	56.	365.	447.	11
12	2	RATED / 2600.	8.	4.0	.303	23.33	40.	.921	375.	926.	2.94	290.	103.	512.	241.	12
13		IDLE / 608.	0.	.0	.050	4.90	40.	.913	560.	1484.	1.43	190.	47.	254.	48.	13

MODE	CALCULATED GRAMS/LB-FUEL HC	CALCULATED GRAMS/LB-FUEL CO	CALCULATED GRAMS/LB-FUEL NOX	GRAMS/BHP-HR HC	GRAMS/BHP-HR CO	GRAMS/BHP-HR NOX	F/A DRY MEAS	F/A STOICH	"PHI"	WET HC CORR FACT	F/A CALC	F/A PCT MEAS	POWER CORR FACT	BSFC CORR LB/HP-HR	MODAL WEIGHT FACTOR	MODE
1	13.20	86.35	20.44	******	******	******	.0098	.0706	.139	.987	.0071	-27.5	.983	*****	.067	1
2	11.91	47.19	17.67	35.52	140.75	52.71	.0100	.0706	.142	.979	.0111	10.3	.991	3.009	.080	2
3	3.52	15.12	18.33	1.78	7.64	9.27	.0185	.0706	.262	.966	.0198	6.9	.992	.510	.080	3
4	1.89	6.36	18.30	.75	2.53	7.29	.0266	.0706	.377	.953	.0276	3.7	.997	.400	.080	4
5	1.52	5.15	20.63	.53	1.80	7.20	.0311	.0706	.441	.948	.0309	-.5	1.001	.349	.080	5
6	1.17	7.29	16.68	.42	2.63	6.01	.0380	.0706	.538	.931	.0417	9.8	1.006	.358	.080	6
7	13.38	77.59	19.64	******	******	******	.0100	.0706	.142	.988	.0071	-29.6	.989	*****	.067	7
8	1.08	8.24	16.71	.45	3.41	6.91	.0354	.0706	.502	.937	.0377	6.4	1.050	.394	.080	8
9	1.20	6.23	16.42	.52	2.69	7.09	.0326	.0706	.461	.945	.0329	1.1	1.038	.416	.080	9
10	1.25	5.81	15.03	.59	2.75	7.11	.0269	.0706	.381	.953	.0275	2.3	1.024	.461	.080	10
11	1.82	11.94	14.60	1.11	7.31	8.94	.0201	.0706	.285	.964	.0209	3.7	1.016	.602	.080	11
12	5.68	28.15	13.25	26.11	129.37	60.91	.0131	.0706	.185	.975	.0143	9.1	1.010	4.551	.080	12
13	15.74	84.73	16.16	******	******	******	.0103	.0706	.145	.987	.0076	-25.4	.987	*****	.067	13

CYCLE COMPOSITE USING 13-MODE WEIGHT FACTORS

BSHC ------- = .983 GRAM/BHP-HR
BSCO ------- = 5.069 GRAM/BHP-HR
BSNOX ------ = 7.701 GRAM/BHP-HR
BSHC + BSNOX = 8.683 GRAM/BHP-HR
CORR. BSFC - = .450 LBS/BHP-HR

TABLE C-4. SUPPLEMENTARY ENGINE DATA OBTAINED OVER 13-MODE TESTING ON (EM-584-F) SUPERIOR CRUDE SHALE OIL

Test	Fuel			Inlet Air			Exhaust		Oil	
Mode No.	Temp.[a] °F	Press.[b] psi	Injector Temp.[c] ° F	Temp. °F	Restrict. in. H_2O	Boost psi	Temp. °F	B.P. in. Hg	Temp. ° F	Press. psi
1	223	35.0	294	77	1.1	0	286	0	188	20
2	202	43.0	293	75	5.6	0.8	348	0.15	198	48
3	234	48.5	291	75	5.9	1.5	508	0.2	202	47
4	270	50.0	291	77	6.8	3.2	670	0.3	207	46.5
5	293	50.0	291	77	8.1	5.5	821	0.4	211	45.5
6	304	48.5	291	78	9.6	8.2	1004	1.7	213	44
7	280	35.0	291	82	1.0	0	390	0	196	19
8	296	55.0	291	79	25.2	15.7	1048	2.3	230	49
9	300	56.0	291	79	21.0	11.7	942	1.8	231	46.5
10	280	56.0	290	78	16.5	7.5	812	1.2	227	47.5
11	259	55.0	289	79	13.0	4.1	675	0.85	221	48
12	253	56.0	289	78	10.9	2.1	523	0.5	216	49.5
13	237	26.0	289	80	1.0	0	278	0	194	19

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[a] Measured at fuel inlet to pump

[b] Measured after secondary filter

[c] Measured approximately 2 inches upstream of injector No. 1

TABLE C-5. REGULATED EMISSIONS SUMMARY FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-584-F) SUPERIOR

Test No.	Run No.	Transient Emissions, g/kW-hr (g/hp-hr) HC	CO	NO_x	Part.	Cycle BSFC kg/kW-hr (lb/hp-hr)	Cycle Work[a] kW-hr (hp-hr)
2	1	2.17 (1.62)	6.44 (4.80)	10.69 (7.97)	3.18 (2.37)	0.279 (0.458)	9.31 (12.48)
2	2	2.12 (1.58)	6.88 (5.13)	10.94 (8.16)	3.04 (2.27)	0.286 (0.471)	9.29 (12.46)

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[a] All runs met statistical criteria

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                    TABLE      ENGINE EMISSION RESULTS
                                      H-TRANS.                                    PROJECT NO. 03-7338-004

ENGINE  NO.1                                TEST NO.2      RUN1
ENGINE  MODEL    0 IHC DT466B               DATE  3/19/84
ENGINE  7.6 L(466. CID) L-6                 TIME                             DIESEL   EM-584-F
CVS NO.  11                                 DYNO NO.  1                      BAG CART NO.  1

BAROMETER 738.38 MM HG(29.07 IN HG)         RELATIVE HUMIDITY ,  ENGINE-58. PCT ,  CVS-30. PCT
DRY BULB TEMP. 23.3 DEG C(74.0 DEG F)       ABSOLUTE HUMIDITY 10.7 GM/KG( 75.1 GRAINS/LB)     NOX HUMIDITY C.F. 1.0000

BAG RESULTS
   BAG NUMBER                                    1                 2                 3                 4
   DESCRIPTION                                 NYNF              LANF               LAF              NYNF
   TIME SECONDS                                296.0             300.0             305.0             298.0
   TOT. BLOWER RATE SCMM (SCFM)          82.33 ( 2907.2)   82.32 ( 2906.6)   82.33 ( 2906.9)   82.32 ( 2906.7)
   TOT. 20X20 RATE SCMM (SCFM)            8.58 (302.9)      8.58 (302.9)      8.58 (302.9)      8.58 (302.9)
   TOT. 90MM RATE SCMM (SCFM)              .02 (   .77)      .02 (   .77)      .02 (   .77)      .02 (   .77)
   TOT. AUX. SAMPLE RATE SCMM (SCFM)       .02 (   .69)      .02 (   .69)      .02 (   .69)      .02 (   .69)
   TOTAL FLOW STD. CU. METRES(SCF)       448.7 (  15844.)  454.7 (16055.)    462.3 (16324.)    451.7 (15948.)

   HC   SAMPLE METER/RANGE/PPM           18.9/22/  19.     25.1/22/  25.     28.6/22/  29.     27.4/22/  27.
   HC   BCKGRD METER/RANGE/PPM            5.5/ 2/   6.      5.9/ 2/   6.      6.2/ 2/   6.      6.0/ 2/   6.
   CO   SAMPLE METER/RANGE/PPM           29.5/13/  27.     33.4/13/  31.     35.7/13/  33.     29.9/13/  27.
   CO   BCKGRD METER/RANGE/PPM            1.1/13/   1.      1.0/13/   1.      1.1/13/   1.       .9/13/   1.
   CO2  SAMPLE METER/RANGE/PCT           73.7/13/  .15     56.3/12/  .22     65.5/11/  .56     73.8/13/  .15
   CO2  BCKGRD METER/RANGE/PCT           20.9/13/  .04     11.6/12/  .04      6.7/11/  .04     20.4/13/  .04
   NOX  SAMPLE METER/RANGE/PPM           52.3/ 1/  16.     73.1/ 1/  22.     62.0/ 2/  62.     50.6/ 1/  15.
   NOX  BCKGRD METER/RANGE/PPM             .5/ 1/   0.       .3/ 1/   0.       .3/ 2/   0.       .6/ 1/   0.

   DILUTION FACTOR                            85.85             58.41             23.74             85.24
   HC   CONCENTRATION PPM                     13.               19.               23.               21.
   CO   CONCENTRATION PPM                     26.               30.               31.               26.
   CO2  CONCENTRATION PCT                     .11               .19               .52               .11
   NOX  CONCENTRATION PPM                     15.4              21.7              61.7              14.9

   HC   MASS GRAMS                            3.49              5.06              6.04              5.59
   CO   MASS GRAMS                           13.47             15.62             16.91             13.85
   CO2  MASS GRAMS                           933.0             1542.1            4400.7            949.2
   NOX  MASS GRAMS                           13.22             18.83             54.56             12.85
   FUEL KG (LB)                           .313 (    .69)   .514 (   1.13)   1.443 (   3.18)    .321 (    .71)
   KW HR (HP HR)                           .99 (   1.33)   1.80 (   2.41)    5.52 (   7.40)    1.00 (   1.34)

   BSHC G/KW HR (G/HP HR)                 3.52 (   2.62)   2.82 (   2.10)    1.10 (    .82)    5.60 (   4.17)
   BSCO G/KW HR (G/HP HR)                13.59 (  10.13)   8.69 (   6.48)    3.07 (   2.29)   13.86 (  10.34)
   BSCO2 G/KW HR (G/HP HR)              940.76 ( 701.52) 858.11 ( 639.89)  797.49 ( 594.69)  949.95 ( 708.38)
   BSNOX G/KW HR (G/HP HR)               13.33 (   9.94)  10.48 (   7.81)    9.89 (   7.37)   12.86 (   9.59)
   BSFC KG/KW HR (LB/HP HR)               .316 (   .519)   .286 (   .470)    .262 (   .430)    .321 (   .528)

TOTAL TEST RESULTS 4 BAGS                              PARTICULATE RESULTS, TOTAL FOR 4 BAGS

   TOTAL KW HR (HP HR)          9.31 (  12.48)         90MM PARTICULATE RATES    GRAMS/TEST                29.62
   BSHC   G/KW HR (G/HP HR)     2.17 (   1.62)                                   G/KWHR(G/HPHR)        3.18  ( 2.37)
   BSCO   G/KW HR (G/HP HR)     6.43 (   4.80)                                   G/KG FUEL (G/LB FUEL) 11.43  ( 5.19)
   BSCO2  G/KW HR (G/HP HR)     841. (   627.)                                   FILTER EFF.               93.1
   BSNOX  G/KW HR (G/HP HR)    10.69 (   7.97)
   BSFC   KG/KW HR (LB/HP HR)   .278 (   .458)
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                    TABLE       ENGINE EMISSION RESULTS
                                      H-TRANS.                                    PROJECT NO. 03-7338-004

ENGINE  NO.1                             TEST NO.2       RUN2
ENGINE  MODEL    0 IHC DT466B            DATE  3/19/84
ENGINE  7.6 L(466. CID) L-6              TIME                                 DIESEL    EM-584-F
CVS NO.  11                              DYNO NO.  1                          BAG CART NO.  1

BAROMETER 738.12 MM HG(29.06 IN HG)      RELATIVE HUMIDITY ,  ENGINE-53. PCT ,  CVS-30. PCT
DRY BULB TEMP. 23.9 DEG C(75.0 DEG F)    ABSOLUTE HUMIDITY 10.1 GM/KG( 70.9 GRAINS/LB)     NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                    1                2                3                4
  DESCRIPTION                                 NYNF             LANF              LAF             NYNF
  TIME SECONDS                               296.0            300.0            305.0            298.0
  TOT. BLOWER RATE SCMM (SCFM)          82.28 ( 2905.4)  82.31 ( 2906.2)  82.29 ( 2905.8)  82.28 ( 2905.3)
  TOT. 20X20 RATE SCMM (SCFM)           8.66 (305.8)     8.66 (305.8)     8.66 (305.8)     8.66 (305.8)
  TOT. 90MM RATE SCMM (SCFM)             .02 (  .56)      .02 (  .56)      .02 (  .56)      .02 (  .56)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)      .02 (  .83)      .02 (  .83)      .02 (  .83)      .02 (  .83)
  TOTAL FLOW STD. CU. METRES(SCF)       448.8 ( 15849.)  455.0 (16067.)   462.6 (16333.)   451.9 (15955.)

  HC  SAMPLE METER/RANGE/PPM            20.4/22/  20.    26.4/22/  26.    29.6/22/  30.    28.1/22/  28.
  HC  BCKGRD METER/RANGE/PPM             9.5/ 2/  10.     6.8/ 2/   7.     7.0/ 2/   7.     7.0/ 2/   7.
  CO  SAMPLE METER/RANGE/PPM            30.4/13/  28.    36.8/13/  34.    40.2/13/  37.    31.0/13/  29.
  CO  BCKGRD METER/RANGE/PPM             1.6/13/   1.     1.7/13/   2.     1.5/13/   1.     1.4/13/   1.
  CO2 SAMPLE METER/RANGE/PCT            74.7/13/  .15    58.8/12/  .24    66.4/11/  .57    74.2/13/  .15
  CO2 BCKGRD METER/RANGE/PCT            20.9/13/  .04    11.6/12/  .04     6.7/11/  .04    20.9/13/  .04
  NOX SAMPLE METER/RANGE/PPM            52.9/ 1/  16.    78.0/ 1/  23.    64.1/ 2/  64.    51.1/ 1/  15.
  NOX BCKGRD METER/RANGE/PPM             3.3/ 1/   1.     1.5/ 1/   0.      .5/ 2/   1.     1.1/ 1/   0.

  DILUTION FACTOR                            84.44            55.43            23.29            84.64
  HC  CONCENTRATION PPM                      11.              20.              23.              21.
  CO  CONCENTRATION PPM                      26.              32.              35.              27.
  CO2 CONCENTRATION PCT                      .12              .20              .53              .11
  NOX CONCENTRATION PPM                      14.8             22.8             63.6             14.9

  HC  MASS GRAMS                             2.85             5.16             6.11             5.51
  CO  MASS GRAMS                            13.69            17.02            19.04            14.17
  CO2 MASS GRAMS                            952.9           1642.7           4493.3            949.5
  NOX MASS GRAMS                            12.68            19.81            56.28            12.86
  FUEL KG (LB)                         .319 (     .70)  .547 (    1.21)  1.474 (    3.25)  .321 (     .71)
  KW HR (HP HR)                        1.00 (    1.34)  1.78 (    2.39)  5.51 (    7.39)  1.00 (    1.34)

  BSHC G/KW HR (G/HP HR)               2.85 (    2.12)  2.90 (    2.16)  1.11 (     .83)  5.52 (    4.11)
  BSCO G/KW HR (G/HP HR)              13.70 (   10.21)  9.55 (    7.12)  3.46 (    2.58) 14.18 (   10.57)
  BSCO2 G/KW HR (G/HP HR)            953.63 (  711.12) 921.70 (  687.31) 815.37 (  608.02) 950.19 (  708.56)
  BSNOX G/KW HR (G/HP HR)             12.69 (    9.46) 11.12 (    8.29) 10.21 (    7.62) 12.87 (    9.59)
  BSFC KG/KW HR (LB/HP HR)             .319 (    .525)  .307 (    .505)  .268 (    .440)  .321 (    .528)

TOTAL TEST RESULTS 4 BAGS                            PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)          9.29 ( 12.46)         90MM PARTICULATE RATES    GRAMS/TEST              28.23
  BSHC   G/KW HR (G/HP HR)     2.11 (  1.58)                                   G/KWHR(G/HPHR)       3.04  ( 2.27)
  BSCO   G/KW HR (G/HP HR)     6.88 (  5.13)                                   G/KG FUEL (G/LB FUEL) 10.61  ( 4.81)
  BSCO2  G/KW HR (G/HP HR)     865. (  645.)                                   FILTER EFF.             95.6
  BSNOX  G/KW HR (G/HP HR)    10.94 (  8.16)
  BSFC   KG/KW HR (LB/HP HR)   .286 (  .471)
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TABLE C-8. INDIVIDUAL HYDROCARBONS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-584-F) SUPERIOR CRUDE SHALE OIL

Individual HC from Test 2, Run 1, 3/19/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	540	58	220
Ethylene	1700	180	680
Ethane	79	8.5	32
Acetylene	130	14	51
Propane	0	0	0
Propylene	580	63	230
Benzene	150	16	59
Toluene	0	0	0

Individual HC from Test 2, Run 2, 3/19/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	560	60	220
Ethylene	1700	180	660
Ethane	91	9.8	35
Acetylene	120	13	46
Propane	0	0	0
Propylene	640	68	250
Benzene	170	18	65
Toluene	0	0	0

TABLE C-9. ALDEHYDES FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-584-F) SUPERIOR CRUDE SHALE OIL

Aldehydes from Test 2, Run 1, 3/19/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	450	48	180
Acetaldehyde	570	61	230
Acrolein	110	12	45
Acetone	620	66	250
Propionaldehyde	0	0	0
Crotonaldehyde	15	1.6	5.9
Isobutyraldehyde & Methylethylketone	170	18	69
Benzaldehyde	36	3.8	14
Hexanaldehyde	36	3.9	14

Aldehydes from Test 2, Run 2, 3/19/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1400	150	530
Acetaldehyde	860	93	330
Acrolein	380	41	150
Acetone	390	42	150
Propionaldehyde	140	16	56
Crotonaldehyde	140	15	53
Isobutyraldehyde & Methylethylketone	380	40	150
Benzaldehyde	97	10	37
Hexanaldehyde	130	14	52

TABLE C-10. PHENOLS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-584-F) SUPERIOR CRUDE SHALE OIL

Phenols from Test 2, Run 1, 3/19/84

Phenol	mg/test	mg/kW-hr	mg/kg fuel
Phenol	0	0	0
Salicylaldehyde	0	0	0
M- & P-cresol	0	0	0
Five[a]	0	0	0
TNPPH[b]	0	0	0
TR235[c]	40	4.3	16
T2356[d]	0	0	0

Phenols from Test 2, Run 2, 3/19/84

No Phenols above background levels detected

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[a] p-ethylphenol, 2-isopropylphenol, 2,3-xylenol, 3,5-xylenol, 2,4,6-trimethylphenol

[b] 2-n-propylphenol

[c] 2,3,5-trimethylphenol

[d] 2,3,5,6-tetramethylphenol

TABLE C-11. SUMMARY OF TIA BY DOAS[a] FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-584-F) SUPERIOR CRUDE SHALE OILS

Test No.	Run No.	LCA μg/ℓ	TIA[b]	LCO μg/ℓ	TIA[c]
2	1	22.61	1.35	57.32	2.76
2	2	22.38	1.34	19.54	2.29

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[a] These measurements were based on DOAS standard corresponding for use of No. 2 diesel fuel. Samples were taken from dilute exhaust of approximately 12:1 for the overall transient cycle.

[b] TIA based on liquid column aromatics (LCA) by:
$\text{TIA} = 0.4 + 0.7 \log_{10} (\text{LCA})$

[c] TIA based on liquid column oxygenates (LCO) by:
$\text{TIA} = 1 + \log_{10} (\text{LCO})$, (TIA by LCO perferred)

C-12. FEDERAL SMOKE TEST TRACE EVALUATION

Engine Model: DT-466 B Test No. 2 Date: 3/20/84

Engine S/N: Fuel EM-584-F Run No. 1 Eval. By: K Jack

Observed Power: 193 hp

Barometer: 29.23 in. Hg.

Accelerations

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	51.5	1	74.5	1	53.0
2	77.0	2	89.3	2	99.0
3	41.0	3	60.0	3	83.0
4	27.5	4	37.5	4	46.0
5	29.0	5	38.0	5	41.0
6	34.0	6	40.0	6	44.0
7	28.5	7	42.0	7	52.0
8	20.5	8	27.0	8	40.0
9	15.0	9	28.0	9	31.0
10	21.0	10	16.0	10	19.0
11	18.0	11	21.3	11	23.5
12	14.0	12	18.0	12	19.0
13	13.7	13	15.0	13	15.0
14	12.5	14	15.0	14	16.5
15	13.2	15	15.0	15	18.0

Total Smoke % 416.4 536.6 600.0

Factor (a) = $\frac{1553.0}{45}$ = 34.5

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	10.7	1	10.7	1	11.0
2	10.2	2	11.0	2	11.0
3	11.0	3	10.8	3	11.0
4	10.3	4	10.8	4	10.5
5	10.3	5	11.3	5	9.8

Total Smoke % 52.5 54.6 53.3

Factor (b) = $\frac{160.4}{15}$ = 10.7 %

Peak

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	77.0	1	89.3	1	99.0
2	51.5	2	74.5	2	83.0
3	41.0	3	60.0	3	53.0

Total Smoke % 169.5 223.0 235.0

Factor (c) = $\frac{627.5}{9}$ = 69.7 %

APPENDIX D

RESULTS FROM OPERATION ON EM-585-F, PARAHO DOE

TABLE D-1

13-MODE FEDERAL DIESEL EMISSION CYCLE 1979

ENGINE: IHC 466B SHALE OIL: PARAHO H/C 1.59 BAROMETER: 29.04
TEST-4-1 FUEL: EM-585-F PROJECT: 03-7338-004 DATE: 3/28/84

MODE	POWER PCT	ENGINE SPEED COND / RPM	TORQUE OBS LB-FT	POWER OBS BHP	FUEL FLOW LB/MIN	AIR FLOW LB/MIN	INTAKE HUMID GR/LB	NOX CORR FACT	MEASURED HC PPM	MEASURED CO PPM	MEASURED CO2 PCT	MEASURED NOX PPM	CALCULATED GRAMS / HOUR HC	CALCULATED GRAMS / HOUR CO	CALCULATED GRAMS / HOUR NOX	MODE
1		IDLE / 625.	0.	.0	.037	4.96	30.	.875	435.	1171.	1.13	165.	34.	186.	37.	1
2	2	INTER / 1800.	9.	3.1	.155	15.37	30.	.888	435.	1088.	1.99	285.	87.	440.	167.	2
3	25	INTER / 1800.	100.	34.3	.295	15.64	30.	.897	240.	718.	3.91	580.	50.	296.	350.	3
4	50	INTER / 1800.	200.	68.5	.442	16.95	30.	.905	190.	373.	6.11	800.	39.	150.	473.	4
5	75	INTER / 1800.	301.	103.2	.657	19.13	30.	.912	175.	350.	7.60	975.	43.	168.	697.	5
6	100	INTER / 1800.	392.	134.3	.853	21.26	30.	.919	175.	542.	8.79	1075.	49.	292.	869.	6
7		IDLE / 630.	0.	.0	.037	4.94	30.	.872	285.	1088.	1.21	200.	21.	166.	43.	7
8	100	RATED / 2600.	382.	189.1	1.373	36.36	30.	.917	200.	641.	8.18	1050.	96.	596.	1462.	8
9	75	RATED / 2600.	300.	148.5	1.023	32.83	26.	.901	195.	327.	7.14	875.	80.	260.	1024.	9
10	50	RATED / 2600.	200.	99.0	.815	28.30	26.	.899	158.	327.	5.86	663.	62.	252.	751.	10
11	25	RATED / 2600.	100.	49.5	.520	24.74	26.	.888	165.	350.	4.38	475.	55.	230.	452.	11
12	2	RATED / 2600.	8.	4.0	.307	22.64	26.	.882	400.	887.	2.72	290.	120.	534.	251.	12
13		IDLE / 625.	0.	.0	.037	4.94	26.	.865	510.	1325.	1.21	165.	37.	195.	34.	13

MODE	CALCULATED GRAMS/LB-FUEL HC	CALCULATED GRAMS/LB-FUEL CO	CALCULATED GRAMS/LB-FUEL NOX	CALCULATED GRAMS/BHP-HR HC	CALCULATED GRAMS/BHP-HR CO	CALCULATED GRAMS/BHP-HR NOX	F/A DRY MEAS	F/A STOICH	"PHI"	WET HC CORR FACT	F/A CALC	F/A PCT MEAS	POWER CORR FACT	BSFC CORR LB/HP-HR	MODAL WEIGHT FACTOR	MODE
1	15.45	84.62	17.03	*************		******	.0074	.0705	.105	.989	.0060	-18.6	.997	*****	.067	1
2	9.37	47.36	17.98	28.25	142.80	54.22	.0101	.0705	.144	.982	.0100	-1.2	1.005	3.001	.080	2
3	2.81	16.72	19.77	1.45	8.63	10.21	.0189	.0705	.269	.968	.0186	-2.1	1.005	.514	.080	3
4	1.47	5.64	17.87	.57	2.18	6.91	.0262	.0705	.371	.952	.0283	8.2	1.008	.384	.080	4
5	1.10	4.27	17.70	.42	1.63	6.76	.0345	.0705	.489	.942	.0349	1.3	1.012	.377	.080	5
6	.96	5.71	16.97	.37	2.17	6.47	.0403	.0705	.572	.933	.0403	-.1	1.017	.375	.080	6
7	9.70	75.32	19.70	*************		******	.0074	.0705	.106	.989	.0063	-15.3	.998	*****	.067	7
8	1.17	7.23	17.74	.51	3.15	7.73	.0379	.0705	.538	.937	.0376	-.8	1.057	.412	.080	8
9	1.30	4.24	16.68	.54	1.75	6.90	.0313	.0705	.444	.945	.0329	5.1	1.047	.395	.080	9
10	1.27	5.16	15.36	.63	2.55	7.59	.0289	.0705	.410	.954	.0271	-6.1	1.032	.478	.080	10
11	1.75	7.37	14.49	1.10	4.64	9.13	.0211	.0705	.299	.965	.0205	-2.9	1.025	.615	.080	11
12	6.52	29.04	13.66	30.27	134.91	63.47	.0136	.0705	.193	.977	.0133	-2.5	1.018	4.564	.080	12
13	16.78	88.67	15.58	*************		******	.0074	.0705	.106	.989	.0065	-12.4	.997	*****	.067	13

CYCLE COMPOSITE USING 13-MODE WEIGHT FACTORS

BSHC ------- = .910 GRAM/BHP-HR
BSCO ------- = 4.412 GRAM/BHP-HR
BSNOX ------ = 7.911 GRAM/BHP-HR
BSHC + BSNOX = 8.821 GRAM/BHP-HR
CORR. BSFC - = .456 LBS/BHP-HR

TABLE D-2. SUPPLEMENTARY ENGINE DATA OBTAINED OVER 13-MODE TESTING ON (EM-585-F) PARAHO DOE CRUDE SHALE OIL

Test Mode No.	Fuel			Inlet Air			Exhaust		Oil	
	Temp.[a] °F	Press.[b] psi	Injector Temp.[c] ° F	Temp. °F	Restrict. in. H_2O	Boost psi	Temp. ° F	B.P. in. Hg	Temp. ° F	Press. psi
1	265	42.0	280	82	1.0	0	300	0	198	d
2	211	51.0	272	79	5.6	0.7	341	0.2	199	d
3	202	46.0	278	79	5.8	1.2	487	0.3	202	d
4	210	45.0	280	79	6.55	2.8	665	0.4	206	d
5	238	47.5	280	80	7.9	5.2	828	0.6	211	d
6	254	48.0	280	80	9.6	8.1	972	0.85	214	d
7	272	43.5	281	83	1.0	0	390	0	200	d
8	244	52.5	281	79	24.8	15.2	1040	2.6	223	d
9	278	61.0	280	80	20.6	11.7	942	2.0	231	d
10	269	65.0	282	79	15.8	7.0	804	1.4	226	d
11	259	67.0	282	80	12.6	3.8	664	0.9	222	d
12	238	66.5	282	79	10.5	1.8	503	0.65	217	d
13	229	38.5	280	82	1.0	0	286	0	199	d

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[a] Measured at fuel inlet to pump

[b] Measured after secondary filter

[c] Measured approximately 2 inches upstream of injector No. 1

[d] No data

TABLE D-3. REGULATED EMISSIONS SUMMARY FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-585-F) PARAHO DOE

Test No.	Run No.	Transient Emissions, g/kW-hr (g/hp-hr) HC	CO	NO_x	Part.	Cycle BSFC kg/kW-hr (lb/hp-hr)	Cycle Work[a] kW-hr (hp-hr)
4	1	2.31 (1.72)	5.69 (4.24)	11.71 (8.73)	2.79 (2.08)	0.272 (0.447)	9.42 (12.63)
4	2	2.28 (1.70)	5.63 (4.20)	11.83 (8.82)	2.92 (2.18)	0.271 (0.445)	9.38 (12.58)

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[a] All runs met statisticla criteria

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                        TABLE        ENGINE EMISSION RESULTS
                                          H-TRANS.                               PROJECT NO. 03-7338-004

ENGINE  NO.                                  TEST NO.4       RUN1
ENGINE  MODEL    0 IHC DT466B                DATE  3/28/84
ENGINE  7.6 L(466. CID) L-6                  TIME                              DIESEL   EM-585-F
CVS NO.  11                                  DYNO NO.  1                       BAG CART NO.  1

BAROMETER 738.63 MM HG(29.08 IN HG)          RELATIVE HUMIDITY ,  ENGINE-55. PCT ,  CVS-29. PCT
DRY BULB TEMP. 22.8 DEG C(73.0 DEG F)        ABSOLUTE HUMIDITY  9.8 GM/KG( 68.7 GRAINS/LB)      NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                    1                   2                   3                   4
  DESCRIPTION                                 NYNF                LANF                 LAF                NYNF
  TIME SECONDS                                296.0               300.0               305.0               298.0
  TOT. BLOWER RATE SCMM (SCFM)           81.08 ( 2863.0)     81.06 ( 2862.4)     81.06 ( 2862.3)     81.04 ( 2861.5)
  TOT. 20X20 RATE SCMM (SCFM)             8.67 (306.2)        8.67 (306.2)        8.67 (306.2)        8.67 (306.2)
  TOT. 90MM RATE SCMM (SCFM)               .02 (   .57)        .02 (   .57)        .02 (   .57)        .02 (   .57)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)        .03 ( 1.19)         .03 ( 1.19)         .03 ( 1.19)         .03 ( 1.19)
  TOTAL FLOW STD. CU. METRES(SCF)        443.0 (  15643.)    448.9 (15852.)      456.4 (16116.)      445.8 (15742.)

  HC  SAMPLE METER/RANGE/PPM             29.3/22/  29.       27.2/22/  27.       29.5/22/  29.       26.1/22/  26.
  HC  BCKGRD METER/RANGE/PPM              8.0/ 2/   8.        6.7/ 2/   7.        7.0/ 2/   7.        7.1/ 2/   7.
  CO  SAMPLE METER/RANGE/PPM             31.1/13/  29.       31.6/13/  29.       27.7/13/  25.       26.3/13/  24.
  CO  BCKGRD METER/RANGE/PPM               .7/13/   1.         .8/13/   1.        1.0/13/   1.         .9/13/   1.
  CO2 SAMPLE METER/RANGE/PCT             73.8/13/  .15       57.0/12/  .23       66.0/11/  .56       74.3/13/  .15
  CO2 BCKGRD METER/RANGE/PCT             20.0/13/  .04       10.7/12/  .04        6.6/11/  .04       19.9/13/  .04
  NOX SAMPLE METER/RANGE/PPM             53.9/ 1/  16.       82.0/ 1/  24.       71.2/ 2/  71.       58.2/ 1/  17.
  NOX BCKGRD METER/RANGE/PPM              1.0/ 1/   0.        1.8/ 1/   1.         .4/ 2/   0.         .8/ 1/   0.

  DILUTION FACTOR                           85.07               57.57               23.84               84.85
  HC  CONCENTRATION PPM                     21.                 21.                 23.                 19.
  CO  CONCENTRATION PPM                     28.                 28.                 24.                 23.
  CO2 CONCENTRATION PCT                      .12                 .19                 .52                 .12
  NOX CONCENTRATION PPM                     15.7                23.9                70.8                17.1

  HC  MASS GRAMS                             5.47                5.33                5.99                4.92
  CO  MASS GRAMS                            14.26               14.64               12.77               11.93
  CO2 MASS GRAMS                           937.4              1575.6              4348.3               954.5
  NOX MASS GRAMS                            13.34               20.49               61.81               14.56
  FUEL KG (LB)                          .314 (     .69)    .519 (    1.14)    1.411 (    3.11)    .318 (     .70)
  KW HR (HP HR)                         1.01 (    1.36)    1.80 (    2.41)     5.59 (    7.50)    1.01 (    1.36)

  BSHC G/KW HR (G/HP HR)                5.40 (    4.03)    2.97 (    2.21)     1.07 (     .80)    4.85 (    3.62)
  BSCO G/KW HR (G/HP HR)               14.07 (   10.49)    8.14 (    6.07)     2.28 (    1.70)   11.77 (    8.77)
  BSCO2 G/KW HR (G/HP HR)             924.28 (  689.23)  876.73 (  653.78)   777.49 (  579.78)  941.21 (  701.86)
  BSNOX G/KW HR (G/HP HR)              13.15 (    9.81)   11.40 (    8.50)    11.05 (    8.24)   14.36 (   10.71)
  BSFC KG/KW HR (LB/HP HR)              .310 (    .509)    .289 (    .475)     .252 (    .415)    .313 (    .515)

TOTAL TEST RESULTS 4 BAGS                                PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)          9.42 ( 12.63)         90MM PARTICULATE RATES    GRAMS/TEST                    26.30
  BSHC  G/KW HR (G/HP HR)      2.30 (  1.72)                                   G/KWHR(G/HPHR)              2.79  ( 2.08)
  BSCO  G/KW HR (G/HP HR)      5.69 (  4.24)                                   G/KG FUEL (G/LB FUEL)      10.27  ( 4.66)
  BSCO2 G/KW HR (G/HP HR)      830. (  619.)                                   FILTER EFF.                   92.3
  BSNOX G/KW HR (G/HP HR)     11.70 (  8.73)
  BSFC  KG/KW HR (LB/HP HR)    .272 (  .447)
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                    TABLE       ENGINE EMISSION RESULTS
                                     H-TRANS.                            PROJECT NO. 03-7338-004

ENGINE  NO.                         TEST NO.4      RUN2
ENGINE  MODEL    0 IHC DT466B       DATE  3/28/84
ENGINE  7.6 L(466. CID) L-6         TIME                              DIESEL   EM-585-F
CVS NO.  11                         DYNO NO.  1                       BAG CART NO.  1

BAROMETER 738.38 MM HG(29.07 IN HG)         RELATIVE HUMIDITY ,  ENGINE-58. PCT ,  CVS-37. PCT
DRY BULB TEMP. 22.8 DEG C(73.0 DEG F)       ABSOLUTE HUMIDITY 10.4 GM/KG( 72.6 GRAINS/LB)     NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                1                  2                  3                  4
  DESCRIPTION                             NYNF               LANF                LAF               NYNF
  TIME SECONDS                            296.0              300.0              305.0              298.0
  TOT. BLOWER RATE SCMM (SCFM)        81.05 ( 2861.8)    81.05 ( 2861.9)    81.04 ( 2861.5)    81.03 ( 2861.3)
  TOT. 20X20 RATE SCMM (SCFM)          8.64 (305.0)       8.64 (305.0)       8.64 (305.0)       8.64 (305.0)
  TOT. 90MM RATE SCMM (SCFM)            .02 (  .56)        .02 (  .56)        .02 (  .56)        .02 (  .56)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)     .02 (  .80)        .02 (  .80)        .02 (  .80)        .02 (  .80)
  TOTAL FLOW STD. CU. METRES(SCF)     442.6 (  15629.)   448.6 (15841.)     456.1 (16103.)     445.6 (15733.)

  HC  SAMPLE METER/RANGE/PPM          28.2/22/  28.      25.0/22/  25.      27.5/22/  27.      24.6/22/  25.
  HC  BCKGRD METER/RANGE/PPM           6.4/ 2/   6.       5.6/ 2/   6.       5.4/ 2/   5.       5.8/ 2/   6.
  CO  SAMPLE METER/RANGE/PPM          30.9/13/  28.      30.1/13/  28.      27.8/13/  25.      26.3/13/  24.
  CO  BCKGRD METER/RANGE/PPM            .6/13/   1.        .7/13/   1.        .9/13/   1.        .7/13/   1.
  CO2 SAMPLE METER/RANGE/PCT          74.6/13/  .15      56.8/12/  .23      65.4/11/  .55      76.7/13/  .16
  CO2 BCKGRD METER/RANGE/PCT          20.6/13/  .04      10.9/12/  .04       6.5/11/  .04      23.0/13/  .04
  NOX SAMPLE METER/RANGE/PPM          53.9/ 1/  16.      81.9/ 1/  24.      71.7/ 2/  72.      57.9/ 1/  17.
  NOX BCKGRD METER/RANGE/PPM            .8/ 1/   0.        .9/ 1/   0.        .3/ 2/   0.        .1/ 1/   0.

  DILUTION FACTOR                         84.13              57.89              24.15              81.95
  HC  CONCENTRATION PPM                   22.                20.                22.                19.
  CO  CONCENTRATION PPM                   27.                27.                24.                23.
  CO2 CONCENTRATION PCT                    .12                .19                .51                .12
  NOX CONCENTRATION PPM                   15.8               24.1               71.4               17.2

  HC  MASS GRAMS                           5.58               5.05               5.86               4.85
  CO  MASS GRAMS                          14.16              13.90              12.82              11.98
  CO2 MASS GRAMS                         942.5             1561.1             4290.5              951.7
  NOX MASS GRAMS                          13.37              20.68              62.28              14.65
  FUEL KG (LB)                          .316 (    .70)     .514 (   1.13)    1.392 (   3.07)     .317 (    .70)
  KW HR (HP HR)                         1.01 (   1.35)     1.79 (   2.40)     5.58 (   7.48)     1.01 (   1.35)

  BSHC G/KW HR (G/HP HR)                5.54 (   4.13)     2.82 (   2.10)     1.05 (    .78)     4.82 (   3.59)
  BSCO G/KW HR (G/HP HR)               14.07 (  10.49)     7.77 (   5.79)     2.30 (   1.71)    11.90 (   8.88)
  BSCO2 G/KW HR (G/HP HR)             936.26 ( 698.17)   872.26 ( 650.44)   769.21 ( 573.60)   945.38 ( 704.97)
  BSNOX G/KW HR (G/HP HR)              13.29 (   9.91)    11.55 (   8.62)    11.17 (   8.33)    14.55 (  10.85)
  BSFC KG/KW HR (LB/HP HR)              .314 (   .516)     .287 (   .472)     .250 (   .410)     .315 (   .518)

TOTAL TEST RESULTS 4 BAGS                            PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)          9.38 ( 12.58)       90MM PARTICULATE RATES    GRAMS/TEST                27.44
  BSHC  G/KW HR (G/HP HR)      2.27 (  1.70)                                 G/KWHR(G/HPHR)          2.92  ( 2.18)
  BSCO  G/KW HR (G/HP HR)      5.64 (  4.20)                                 G/KG FUEL (G/LB FUEL)  10.81  ( 4.90)
  BSCO2 G/KW HR (G/HP HR)      826. (  616.)                                 FILTER EFF.                94.8
  BSNOX G/KW HR (G/HP HR)     11.83 (  8.82)
  BSFC  KG/KW HR (LB/HP HR)    .271 (  .445)
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TABLE D-6. INDIVIDUAL HYDROCARBONS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-586-F) PARAHO "DOE" CRUDE SHALE OIL

Individual HC from Test 4, Run 1, 3/28/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	240	26	96
Ethylene	1500	160	590
Ethane	78	8.3	31
Acetylene	97	10	38
Propane	0	0	0
Propylene	590	62	230
Benzene	0	0	0
Toluene	0	0	0

Individual HC from Test 4, Run 2, 3/28/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	230	25	91
Ethylene	1600	170	610
Ethane	56	6.0	22
Acetylene	140	14	54
Propane	0	0	0
Propylene	650	69	260
Benzene	110	11	42
Toluene	0	0	0

TABLE D-7. ALDEHYDES FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-585-F) PARAHO "DOE" CRUDE SHALE OIL

Aldehydes from Test 4, Run 1, 3/28/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1200	1300	460
Acetaldehyde	1000	1100	390
Acrolein	430	46	170
Acetone	230	24	90
Propionaldehyde	180	19	69
Crotonaldehyde	170	19	68
Isobutyraldehyde & Methylethylketone	260	28	100
Benzaldehyde	120	12	45
Hexanaldehyde	240	26	95

Aldehydes from Test 4, Run 2, 3/28/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1300	140	530
Acetaldehyde	890	95	350
Acrolein	430	46	170
Acetone	230	25	92
Propionaldehyde	180	20	72
Crotonaldehyde	170	18	66
Isobutyraldehyde & Methylethylketone	220	24	87
Benzaldehyde	190	20	73
Hexanaldehyde	140	15	57

TABLE D-8. PHENOLS FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-585-F) PARAHO DOE CRUDE SHALE OIL

Phenols from Test 4, Run 1, 3/28/84

Phenol	mg/test	mg/kW-hr	mg/kg fuel
Phenol	0	0	0
Salicylaldehyde	0	0	0
M- & P-cresol	0	0	0
Five[a]	49	5.3	19
TNPPH[b]	0	0	0
TR235[c]	0	0	0
T2356[d]	0	0	0

Phenols from Test 4, Run 2, 3/28/84

Phenol	mg/test	mg/kW-hr	mg/kg fuel
Phenol	0	0	0
Salicylaldehyde	97	10	38
M- & P-cresol	0	0	0
Five[a]	0	0	0
TNPPH[b]	0	0	0
TR235[c]	0	0	0
T2356[d]	0	0	0

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[a] p-ethylphenol, 2-isopropylphenol, 2,3-xylenol, 3,5-xylenol, 2,4,6-trimethylphenol

[b] 2-n-propylphenol

[c] 2,3,5-trimethylphenol

[d] 2,3,5,6-tetramethylphenol

TABLE D-9. SUMMARY OF TIA BY DOAS[a] FROM HOT-START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-585-F) PARAHO "DOE" CRUDE SHALE OILS

Test No.	Run No.	LCA µg/ℓ	TIA[b]	LCO µg/ℓ	TIA[c]
4	1	27.68	1.41	24.92	2.40
4	2	23.59	1.36	14.37	2.16

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[a] These measurements were based on DOAS standard corresponding for use of No. 2 diesel fuel. Samples were taken from dilute exhaust of approximately 12:1 for the overall transient cycle.

[b] TIA based on liquid column aromatics (LCA) by:
$\text{TIA} = 0.4 + 0.7 \log_{10} (\text{LCA})$

[c] TIA based on liquid column oxygenates (LCO) by:
$\text{TIA} = 1 + \log_{10} (\text{LCO})$, (TIA by LCO perferred)

TABLE D-10. **FEDERAL SMOKE TEST TRACE EVALUATION**

Engine Model: IH -DT-466 B **Test No.** 4 **Date:** 3/27/84

Engine S/N: Fuel: EM-585-F **Run No.** 1 **Eval. By:** K. Jack

Observed Power: 193 hp Barometer: 28.39 in. Hg

Accelerations

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	49.0	1	47.0	1	52.0
2	87.0	2	97.5	2	95.0
3	50.0	3	69.0	3	77.0
4	27.5	4	42.0	4	31.0
5	25.0	5	33.0	5	30.5
6	19.7	6	34.0	6	37.0
7	25.0	7	43.0	7	38.3
8	34.0	8	36.0	8	26.0
9	24.0	9	24.0	9	22.0
10	10.7	10	25.0	10	21.5
11	13.7	11	12.0	11	16.0
12	17.5	12	22.0	12	26.0
13	12.0	13	16.0	13	19.3
14	10.0	14	13.0	14	15.0
15	10.0	15	13.0	15	13.8
Total Smoke %	415.1		526.5		500.4

Factor (a) = $\frac{1442.0}{45}$ = 32.0 %

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	7.7	1	7.5	1	8.0
2	7.5	2	8.5	2	7.0
3	9.0	3	8.3	3	7.0
4	7.4	4	8.0	4	7.0
5	8.0	5	8.0	5	8.0
Total Smoke %	39.6		40.3		37.0

Factor (b) = $\frac{116.9}{15}$ = 7.8 %

Peak

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	87.0	1	97.5	1	95.0
2	50.0	2	69.0	2	77.0
3	49.0	3	47.0	3	52.0
Total Smoke %	186.0		213.5		224.0

Factor (c) = $\frac{623.5}{9}$ = 69.3 %

APPENDIX E

RESULTS FROM BORESCOPE INSPECTION

TABLE E-1

Borescope Inspection Report No. 1

Date: 2/9/84 Engine Hours: As Rec'd+2 Fuel Code: EM-528-F

Engine Manufacturer/Designation IH / DT466B Serial No. ______

Cylinder Liner No.

1. Good
2. Good
3. Good
4. 20% BP, T ; 5% Streaking AT
5. Good
6. Good

Notes: Liners like new - bright silver finish

Terms:

"Streaking," faint lines (appearing like pencil lines) along the stroke of the cylinder wall

"BP," Bore Polish, a smoothing of the liner with the cross-hatch still visible

"S," Scuffing, roughning of liner with no cross-hatch visible.

"T," Thrust, right side of liner on a right rotation engine

"AT," Anti-Thrust, left side of liner on a right rotation engine

TABLE E-2

Borescope Inspection Report No. 2

Date: 2/15/84 Engine Hours: A.R.+4 Fuel Code: EM-586-F

Engine Manufacturer/Designation IH / DT466B Serial No. ________

Cylinder Liner No.

1. Good
2. Good
3. Good
4. 20% BP, T; 8% light S, AT
5. 5% BP, AT
6. 5% Streaking, T; 10% BP, AT

Notes: Liners have a dull copper finish

Terms:

"Streaking," faint lines (appearing like pencil lines) along the stroke of the cylinder wall

"BP," Bore Polish, a smoothing of the liner with the cross-hatch still visible

"S," Scuffing, roughning of liner with no cross-hatch visible.

"T," Thrust, right side of liner on a right rotation engine

"AT," Anti-Thrust, left side of liner on a right rotation engine

TABLE E-3

Borescope Inspection Report No. 3

Date: 2/23/84 Engine Hours: A.R.+ 7 Fuel Code: EM-584-F

Engine Manufacturer/Designation IH / DT-466-B Serial No. ________

Cylinder Liner No.

1. Good
2. 5% BP, T
3. 10% BP, T
4. 40% S, T ; 5% S, AT
5. 5% S, T
6. Good

Notes: Liners are bright silver again. Tops of pistons look cleaner than during inspection No 2.. Cylinder No. 4 has a large amount of scuffing.

Terms:

"Streaking," faint lines (appearing like pencil lines) along the stroke of the cylinder wall

"BP," Bore Polish, a smoothing of the liner with the cross-hatch still visible

"S," Scuffing, roughning of liner with no cross-hatch visible.

"T," Thrust, right side of liner on a right rotation engine

"AT," Anti-Thrust, left side of liner on a right rotation engine

TABLE E-4

Borescope Inspection Report No. 4

Date: 3/15/84 Engine Hours: A.R.+13 Fuel Code: EM-528-F

Engine Manufacturer/Designation IH / DT466 B Serial No. —

Cylinder Liner No.

1. —, T; 4% BP, AT "–" No Comment
2. —, T; 15% BT, AT
3. —, T; — AT
4. 20% S, T; 50% S, AT
5. — T; 8% S, 5% BP, AT
6. — T; — AT

Notes: Liners are bright silver

Cylinder No. 4 has 70% of cylinder liner circumference scuffed and is thought to be the reason for reduction in max power from 210 to 198 on DF-2.

Terms:

"Streaking," faint lines (appearing like pencil lines) along the stroke of the cylinder wall

"BP," Bore Polish, a smoothing of the liner with the cross-hatch still visible

"S," Scuffing, roughning of liner with no cross-hatch visible.

"T," Thrust, right side of liner on a right rotation engine

"AT," Anti-Thrust, left side of liner on a right rotation engine

TABLE E-5
Borescope Inspection Report No. 5

Date: 3/20/84 Engine Hours: AR + 21 Fuel Code: EM-584-F

Engine Manufacturer/Designation IHC / DT466B Serial No. ______

Cylinder Liner No.

1. 2% S, T; 8% BP, AT
2. Good
3. 15% BP, AT
4. 40% S, T; 35% S, AT
5. 5% S, T; 5% BP, AT
6. Good

Notes: Liner has a dull look

Top of piston is dull black to varnish color - metallic surface still visible

Terms:

"Streaking," faint lines (appearing like pencil lines) along the stroke of the cylinder wall

"BP," Bore Polish, a smoothing of the liner with the cross-hatch still visible

"S," Scuffing, roughning of liner with no cross-hatch visible.

"T," Thrust, right side of liner on a right rotation engine

"AT," Anti-Thrust, left side of liner on a right rotation engine

TABLE E-6

Borescope Inspection Report No. 6

Date: 3/26/84 Engine Hours: A.R.123 Fuel Code: EM-586-F

Engine Manufacturer/Designation IH / DT466B Serial No. —

Cylinder Liner No.

1. Good, T; 2% S, 10% BP, AT
2. Good, T; 10% BP, AT
3. 15% BP, T; Good, AT
4. 30% S, T; 40% S, AT
5. Good, T; 5% S, 15% BP AT
6. 4% BP T; 10% BP, AT

Notes: All cylinder walls have copper colored finish
Top of pistons generally had black to dry gray deposits.
Top of pistons 4, 5 and 6 appear to have "start of hole at the center of piston"
(this may be attributed to the carbon deposit blown off the top of piston)

Terms:

"Streaking," faint lines (appearing like pencil lines) along the stroke of the cylinder wall

"BP," Bore Polish, a smoothing of the liner with the cross-hatch still visible

"S," Scuffing, roughning of liner with no cross-hatch visible.

"T," Thrust, right side of liner on a right rotation engine

"AT," Anti-Thrust, left side of liner on a right rotation engine

TABLE E-7

Borescope Inspection Report No. 7

Date: 3/29/84 Engine Hours: A.R.+30 Fuel Code: EM-585-F

Engine Manufacturer/Designation IH / DT-466B Serial No. —

Cylinder Liner No.

1. 4% BP, T; 2% S, AT
2. 3% BP, T; 5% BP, AT
3. Good, T; 10% BP, AT
4. 40% S, 5% BP, T; 30% S, 5% BP, AT
5. Good, T; 5% S, AT
6. Good, T; Good, AT

Notes: An indentation at the top of the piston crown was noted for each cylinder. Deposits on top of piston where "dark tan", "sandy". All liners had a dull copper colored finish. Two "chunks" of deposits were noted at the base of the piston crown on No4.

Terms:

"Streaking," faint lines (appearing like pencil lines) along the stroke of the cylinder wall

"BP," Bore Polish, a smoothing of the liner with the cross-hatch still visible

"S," Scuffing, roughning of liner with no cross-hatch visible.

"T," Thrust, right side of liner on a right rotation engine

"AT," Anti-Thrust, left side of liner on a right rotation engine

APPENDIX F

RESULTS FROM OPERATION ON EM-597-F, DF-2

TABLE F-1. 13-MODE FEDERAL DIESEL EMISSION CYCLE 1979

ENGINE: IHC DT466B H/C RATIO 1.79 BAROMETER: 29.00
TEST- 5 FUEL: EM-597-F PROJECT: 03-7774-002 DATE: 7/17/84

MODE	POWER PCT	ENGINE SPEED COND / RPM	TORQUE OBS LB-FT	POWER OBS BHP	FUEL FLOW LB/MIN	AIR FLOW LB/MIN	INTAKE HUMID GR/LB	NOX CORR FACT	MEASURED HC PPM	MEASURED CO PPM	MEASURED CO2 PCT	MEASURED NOX PPM	CALCULATED GRAMS / HOUR HC	CALCULATED GRAMS / HOUR CO	CALCULATED GRAMS / HOUR NOX	MODE
1		IDLE / 695.	0.	.0	.037	5.69	64.	.971	290.	350.	1.30	300.	22.	52.	70.	1
2	2	INTER / 1800.	10.	3.4	.143	15.49	64.	.980	303.	327.	1.89	225.	62.	132.	146.	2
3	25	INTER / 1800.	118.	40.4	.315	16.19	64.	.986	235.	258.	3.98	550.	52.	111.	381.	3
4	50	INTER / 1800.	237.	81.2	.518	17.84	66.	.990	208.	136.	6.11	885.	51.	63.	665.	4
5	75	INTER / 1800.	365.	125.1	.763	20.48	66.	.986	210.	158.	7.79	1250.	60.	85.	1081.	5
6	100	INTER / 1800.	473.	162.1	.940	22.17	66.	.984	160.	433.	9.21	1350.	48.	242.	1212.	6
7		IDLE / 698.	0.	.0	.035	5.67	64.	.967	290.	315.	1.25	285.	21.	46.	66.	7
8	100	RATED / 2600.	423.	209.4	1.408	40.37	64.	.985	140.	421.	7.89	1100.	73.	412.	1728.	8
9	75	RATED / 2600.	317.	156.9	.992	31.70	64.	.983	150.	104.	6.92	1000.	62.	82.	1264.	9
10	50	RATED / 2600.	212.	105.0	.718	27.38	62.	.978	160.	93.	5.55	725.	59.	66.	822.	10
11	25	RATED / 2600.	106.	52.5	.472	23.91	62.	.978	185.	158.	4.11	488.	60.	99.	489.	11
12	2	RATED / 2600.	9.	4.5	.253	21.35	62.	.986	270.	258.	2.39	210.	78.	148.	193.	12
13		IDLE / 698.	0.	.0	.037	5.69	64.	.980	325.	327.	1.17	255.	27.	54.	67.	13

MODE	CALCULATED GRAMS/LB-FUEL HC	CALCULATED GRAMS/LB-FUEL CO	CALCULATED GRAMS/LB-FUEL NOX	CALCULATED GRAMS/BHP-HR HC	CALCULATED GRAMS/BHP-HR CO	CALCULATED GRAMS/BHP-HR NOX	F/A DRY MEAS	F/A STOICH	"PHI"	WET HC CORR FACT	F/A CALC	F/A PCT MEAS	POWER CORR FACT	BSFC CORR LB/HP-HR	MODAL WEIGHT FACTOR	MODE
1	9.78	23.58	32.02	******	******	******	.0065	.0691	.094	.985	.0065	-.4	1.000	*****	.067	1
2	7.18	15.39	16.93	18.01	38.61	42.47	.0093	.0691	.135	.980	.0092	-1.0	1.007	2.491	.080	2
3	2.75	5.89	20.18	1.28	2.75	9.43	.0196	.0691	.284	.963	.0189	-3.8	1.007	.464	.080	3
4	1.62	2.03	21.38	.62	.78	8.19	.0293	.0691	.425	.945	.0285	-2.7	1.008	.380	.080	4
5	1.31	1.86	23.61	.48	.68	8.64	.0376	.0691	.545	.932	.0361	-4.1	1.014	.361	.080	5
6	.85	4.29	21.49	.30	1.49	7.48	.0428	.0691	.620	.921	.0425	-.8	1.018	.342	.080	6
7	10.18	22.09	31.53	******	******	******	.0062	.0691	.090	.986	.0062	-.2	1.002	*****	.067	7
8	.86	4.87	20.45	.35	1.97	8.25	.0352	.0691	.510	.931	.0366	4.0	1.056	.382	.080	8
9	1.04	1.38	21.24	.40	.52	8.05	.0316	.0691	.457	.939	.0321	1.8	1.039	.365	.080	9
10	1.37	1.53	19.08	.56	.63	7.83	.0265	.0691	.383	.950	.0260	-1.9	1.029	.399	.080	10
11	2.11	3.50	17.28	1.14	1.89	9.32	.0199	.0691	.288	.962	.0194	-2.5	1.021	.528	.080	11
12	5.13	9.71	12.71	17.52	33.12	43.37	.0120	.0691	.173	.976	.0115	-3.6	1.014	3.364	.080	12
13	12.09	24.33	30.33	******	******	******	.0065	.0691	.094	.987	.0059	-9.8	.998	*****	.067	13

CYCLE COMPOSITE USING 13-MODE WEIGHT FACTORS
BSHC ------- = .703 GRAM/BHP-HR
BSCO ------- = 1.666 GRAM/BHP-HR
BSNOX ------ = 8.668 GRAM/BHP-HR
BSHC + BSNOX = 9.371 GRAM/BHP-HR
CORR. BSFC - = .410 LBS/BHP-HR

TABLE F-2. SUPPLEMENTARY ENGINE DATA OBTAINED OVER 13-MODE TESTING ON (EM-597-F) DF-2

Test Mode No.	Fuel		Inlet Air			Exhaust		Oil	
	Temp.[a] °F	Press.[b] psi	Temp. °F	Restrict. in. H_2O	Boost psi	Temp. °F	B.P. in. H_2O	Temp. °F	Press. psi
1	96	30.0	83	1.1	0	286	0	198	22
2	95	50.0	81	5.0	0.5	315	0.2	192	48
3	94	49.0	79	5.6	1.4	489	0.2	197	48
4	94	48.0	78	6.7	3.8	685	0.3	202	46
5	93	46.5	79	8.3	7.0	850	0.5	207	44
6	94	45.0	80	9.4	10.2	1005	0.7	214	42
7	97	30.0	84	1.1	0	295	0	200	22
8	92	56.5	77	24.8	17.4	994	2.1	213	49
9	96	58.0	79	17.5	11.2	860	1.3	225	47
10	97	59.0	80	13.6	7.0	741	0.9	223	47
11	98	60.5	80	10.5	3.6	600	0.6	218	48
12	98	62.0	78	8.9	1.7	438	0.4	214	49
13	98	30.0	81	1.1	0	289	0	202	21

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[a] Measured at inlet to pump

[b] Measured after secondary filter

TABLE F-3

TRANSIENT ENGINE MAP DATA

Engine Model DT-466B Date 7/16/84 Barometer 29.23 in. Hg

Engine Intake Air 78 °F, Relative Humidity 40 %

Transient Map Results

Speed, rpm	Torque, ft-lb[a]	Speed, rpm	Torque, ft-lb[a]
0	240		
100	240	2300	446
200	240	2400	440
300	240	2500	433
400	240	2600	421
500	240	2700	375
600	240	2800	216
700	240	2900	0
800	250	3000	0
900	265	3100	0
1000	286	3200	0
1100	304	3300	0
1200	328	3400	0
1300	350	3500	0
1400	370	3600	0
1500	439	3700	0
1600	453	3800	0
1700	463	3900	0
1800	473	4000	0
1900	477	4100	0
2000	473	4200	0
2100	467	4300	0
2200	457	4400	0

Idle Speed 692 rpm

Max. Power 208 hp (421 ft-lb) @ 2600 rpm

Max. Torque 477 ft-lb @ 1900 rpm

Transient Cycle Work by Command, hp-hr

Segment 1	Segment 2	Segment 3	Segment 4	Total
1.51	2.65	7.79	1.50	13.45

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                                   TABLE F-4. ENGINE EMISSION RESULTS
                                                C-TRANS.                                  PROJECT NO. 03-7774-002

ENGINE  NO.                                    TEST NO.1      RUN1
ENGINE  MODEL     0 IHC DT466B                 DATE  7/17/84
ENGINE  7.6 L(466. CID) L-6                    TIME                                 DIESEL    EM-597-F
CVS NO.  11                                    DYNO NO.  1                          BAG CART NO.  1

BAROMETER 739.14 MM HG(29.10 IN HG)            RELATIVE HUMIDITY ,  ENGINE-57. PCT ,  CVS-58. PCT
DRY BULB TEMP. 22.2 DEG C(72.0 DEG F)          ABSOLUTE HUMIDITY  9.8 GM/KG( 68.9 GRAINS/LB)      NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                          1                   2                   3                   4
  DESCRIPTION                                        NYNF                LANF                LAF                 NYNF
  TIME SECONDS                                      296.0               300.0               305.0               298.0
  TOT. BLOWER RATE SCMM (SCFM)               82.94 ( 2928.8)     82.93 ( 2928.2)     82.97 ( 2929.8)     82.95 ( 2929.0)
  TOT. 20X20 RATE SCMM (SCFM)                 9.74 (343.9)        9.74 (343.9)        9.74 (343.9)        9.74 (343.9)
  TOT. 90MM RATE SCMM (SCFM)                   .03 (   .91)        .03 (   .91)        .03 (   .91)        .03 (   .91)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)            .05 ( 1.72)         .05 ( 1.72)         .05 ( 1.72)         .05 ( 1.72)
  TOTAL FLOW STD. CU. METRES(SCF)           457.6 (  16158.)    463.7 (16374.)      471.7 (16655.)      460.7 (16268.)

  HC   SAMPLE METER/RANGE/PPM                39.0/21/  20.       36.4/21/  18.       43.2/21/  22.       30.5/21/  15.
  HC   BCKGRD METER/RANGE/PPM                14.0/ 1/   7.       14.6/ 1/   7.       14.2/ 1/   7.       14.2/ 1/   7.
  CO   SAMPLE METER/RANGE/PPM                24.5/13/  22.       18.7/13/  17.       17.6/13/  16.       10.9/13/  10.
  CO   BCKGRD METER/RANGE/PPM                  .6/13/   1.         .9/13/   1.        1.1/13/   1.         .9/13/   1.
  CO2  SAMPLE METER/RANGE/PCT                83.8/13/  .18       60.1/12/  .24       65.9/11/  .56       74.3/13/  .15
  CO2  BCKGRD METER/RANGE/PCT                21.2/13/  .04       12.0/12/  .04        7.1/11/  .04       21.2/13/  .04
  NOX  SAMPLE METER/RANGE/PPM                63.2/ 1/  19.       85.4/ 1/  25.       70.6/ 2/  71.       61.0/ 1/  18.
  NOX  BCKGRD METER/RANGE/PPM                  .4/ 1/   0.        1.0/ 1/   0.         .5/ 2/   1.        1.1/ 1/   0.

  DILUTION FACTOR                               74.20               54.58               23.96               86.21
  HC   CONCENTRATION PPM                        13.                 11.                 15.                  8.
  CO   CONCENTRATION PPM                        21.                 16.                 15.                  9.
  CO2  CONCENTRATION PCT                         .14                 .20                 .52                 .11
  NOX  CONCENTRATION PPM                        18.7                25.1                70.1                17.8

  HC   MASS GRAMS                                3.33                2.95                4.03                2.19
  CO   MASS GRAMS                               11.39                8.54                8.01                4.75
  CO2  MASS GRAMS                             1156.1              1715.4              4458.5               965.1
  NOX  MASS GRAMS                               16.35               22.27               63.25               15.70
  FUEL KG (LB)                              .376 (     .83)    .551 (    1.21)    1.422 (    3.13)     .311 (     .68)
  KW HR (HP HR)                             1.09 (    1.46)    1.88 (    2.52)     5.62 (    7.53)     1.08 (    1.45)

  BSHC G/KW HR (G/HP HR)                    3.05 (    2.28)    1.57 (    1.17)      .72 (     .54)     2.03 (    1.51)
  BSCO G/KW HR (G/HP HR)                   10.46 (    7.80)    4.55 (    3.39)     1.43 (    1.06)     4.39 (    3.28)
  BSCO2 G/KW HR (G/HP HR)                1061.88 (  791.84)  912.84 (  680.71)   794.02 (  592.10)   892.56 (  665.58)
  BSNOX G/KW HR (G/HP HR)                  15.02 (   11.20)   11.85 (    8.84)    11.26 (    8.40)    14.52 (   10.83)
  BSFC KG/KW HR (LB/HP HR)                  .345 (    .567)    .293 (    .482)     .253 (    .416)     .287 (    .472)

 TOTAL TEST RESULTS 4 BAGS                              PARTICULATE RESULTS, TOTAL FOR 4 BAGS

   TOTAL KW HR (HP HR)          9.66 ( 12.96)          90MM PARTICULATE RATES      GRAMS/TEST                  8.30
   BSHC   G/KW HR (G/HP HR)     1.29 (   .96)                                      G/KWHR(G/HPHR)            .86  (  .64)
   BSCO   G/KW HR (G/HP HR)     3.38 (  2.52)                                      G/KG FUEL (G/LB FUEL)    3.12  ( 1.42)
   BSCO2  G/KW HR (G/HP HR)     858. (  640.)                                      FILTER EFF.               94.7
   BSNOX  G/KW HR (G/HP HR)    12.17 (  9.07)
   BSFC   KG/KW HR (LB/HP HR)   .275 (  .452)
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TABLE F-4. ENGINE EMISSION RESULTS (Cont'd)
H-TRANS.

PROJECT NO. 03-7774-002

ENGINE NO.
ENGINE MODEL 0 IHC DT466B
ENGINE 7.6 L(466. CID) L-6
CVS NO. 11

TEST NO.1 RUN1
DATE 7/17/84
TIME
DYNO NO. 1

DIESEL EM-597-F
BAG CART NO. 1

BAROMETER 738.89 MM HG(29.09 IN HG)
DRY BULB TEMP. 22.2 DEG C(72.0 DEG F)

RELATIVE HUMIDITY , ENGINE-57. PCT , CVS-58. PCT
ABSOLUTE HUMIDITY 9.8 GM/KG(68.9 GRAINS/LB) NOX HUMIDITY C.F. 1.0000

BAG RESULTS

BAG NUMBER	1	2	3	4
DESCRIPTION	NYNF	LANF	LAF	NYNF
TIME SECONDS	296.0	300.0	305.0	298.0
TOT. BLOWER RATE SCMM (SCFM)	82.90 (2927.3)	82.89 (2926.8)	82.90 (2927.4)	82.88 (2926.5)
TOT. 20X20 RATE SCMM (SCFM)	9.70 (342.3)	9.70 (342.3)	9.70 (342.3)	9.70 (342.3)
TOT. 90MM RATE SCMM (SCFM)	.03 (.89)	.03 (.89)	.03 (.89)	.03 (.89)
TOT. AUX. SAMPLE RATE SCMM (SCFM)	.05 (1.70)	.05 (1.70)	.05 (1.70)	.05 (1.70)
TOTAL FLOW STD. CU. METRES(SCF)	457.2 (16143.)	463.3 (16358.)	471.1 (16634.)	460.2 (16248.)
HC SAMPLE METER/RANGE/PPM	31.2/21/ 16.	33.9/21/ 17.	42.6/21/ 21.	31.7/21/ 16.
HC BCKGRD METER/RANGE/PPM	14.5/ 1/ 7.	14.6/ 1/ 7.	14.9/ 1/ 7.	14.9/ 1/ 7.
CO SAMPLE METER/RANGE/PPM	15.5/13/ 14.	15.8/13/ 14.	16.7/13/ 15.	11.0/13/ 10.
CO BCKGRD METER/RANGE/PPM	.9/13/ 1.	1.1/13/ 1.	1.2/13/ 1.	1.2/13/ 1.
CO2 SAMPLE METER/RANGE/PCT	72.8/13/ .15	58.0/12/ .23	63.5/11/ .53	74.0/13/ .15
CO2 BCKGRD METER/RANGE/PCT	21.3/13/ .04	11.7/12/ .04	7.0/11/ .04	21.3/13/ .04
NOX SAMPLE METER/RANGE/PPM	56.8/ 1/ 17.	84.8/ 1/ 25.	66.8/ 2/ 67.	59.6/ 1/ 18.
NOX BCKGRD METER/RANGE/PPM	1.0/ 1/ 0.	1.0/ 1/ 0.	.3/ 2/ 0.	1.0/ 1/ 0.
DILUTION FACTOR	87.97	57.01	25.23	86.57
HC CONCENTRATION PPM	8.	10.	14.	8.
CO CONCENTRATION PPM	13.	13.	14.	9.
CO2 CONCENTRATION PCT	.11	.19	.49	.11
NOX CONCENTRATION PPM	16.6	24.9	66.5	17.4
HC MASS GRAMS	2.22	2.62	3.84	2.25
CO MASS GRAMS	6.90	7.04	7.51	4.65
CO2 MASS GRAMS	926.3	1636.9	4215.7	956.2
NOX MASS GRAMS	14.52	22.09	59.92	15.34
FUEL KG (LB)	.299 (.66)	.525 (1.16)	1.344 (2.96)	.308 (.68)
KW HR (HP HR)	1.09 (1.46)	1.89 (2.54)	5.62 (7.54)	1.08 (1.45)
BSHC G/KW HR (G/HP HR)	2.04 (1.52)	1.38 (1.03)	.68 (.51)	2.08 (1.55)
BSCO G/KW HR (G/HP HR)	6.34 (4.73)	3.71 (2.77)	1.34 (1.00)	4.30 (3.21)
BSCO2 G/KW HR (G/HP HR)	850.79 (634.43)	864.22 (644.45)	749.77 (559.11)	884.36 (659.47)
BSNOX G/KW HR (G/HP HR)	13.33 (9.94)	11.66 (8.70)	10.66 (7.95)	14.19 (10.58)
BSFC KG/KW HR (LB/HP HR)	.275 (.452)	.277 (.456)	.239 (.393)	.285 (.468)

TOTAL TEST RESULTS 4 BAGS

TOTAL KW HR (HP HR)	9.69 (12.99)
BSHC G/KW HR (G/HP HR)	1.13 (.84)
BSCO G/KW HR (G/HP HR)	2.69 (2.01)
BSCO2 G/KW HR (G/HP HR)	799. (595.)
BSNOX G/KW HR (G/HP HR)	11.55 (8.61)
BSFC KG/KW HR (LB/HP HR)	.256 (.420)

PARTICULATE RESULTS, TOTAL FOR 4 BAGS

90MM PARTICULATE RATES	GRAMS/TEST	8.04
	G/KWHR(G/HPHR)	.83 (.62)
	G/KG FUEL (G/LB FUEL)	3.25 (1.47)
	FILTER EFF.	94.8

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                    TABLE F-5. ENGINE EMISSION RESULTS
                                  C-TRANS.                                          PROJECT NO. 03-7774-002

ENGINE  NO.                                 TEST NO.1      RUN2
ENGINE  MODEL    0 IHC DT466B               DATE  7/18/84
ENGINE  7.6 L(466. CID) L-6                 TIME                                 DIESEL   EM-597-F
CVS NO.  11                                 DYNO NO.  1                          BAG CART NO.  1

BAROMETER 740.92 MM HG(29.17 IN HG)         RELATIVE HUMIDITY ,  ENGINE-61. PCT ,  CVS-62. PCT
DRY BULB TEMP. 22.2 DEG C(72.0 DEG F)       ABSOLUTE HUMIDITY 10.5 GM/KG( 73.5 GRAINS/LB)     NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                      1                  2                  3                  4
  DESCRIPTION                                   NYNF               LANF                LAF               NYNF
  TIME SECONDS                                  296.0              300.0              305.0              298.0
  TOT. BLOWER RATE SCMM (SCFM)           83.16 ( 2936.5)    83.15 ( 2935.9)    83.15 ( 2936.1)    83.14 ( 2935.6)
  TOT. 20X20 RATE SCMM (SCFM)             9.72 (343.3)       9.72 (343.3)       9.72 (343.3)       9.72 (343.3)
  TOT. 90MM RATE SCMM (SCFM)               .03 (   .90)       .03 (   .90)       .03 (   .90)       .03 (   .90)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)        .05 ( 1.75)        .05 ( 1.75)        .05 ( 1.75)        .05 ( 1.75)
  TOTAL FLOW STD. CU. METRES(SCF)        458.6 (  16193.)   464.7 (16409.)     472.5 (16684.)     461.6 (16299.)

  HC   SAMPLE METER/RANGE/PPM            41.5/21/  21.      40.3/21/  20.      47.9/21/  24.      43.9/21/  22.
  HC   BCKGRD METER/RANGE/PPM            14.7/ 1/   7.      16.1/ 1/   8.      19.0/ 1/  10.      27.0/ 1/  14.
  CO   SAMPLE METER/RANGE/PPM            26.3/13/  24.      20.1/13/  18.      18.1/13/  16.      10.9/13/  10.
  CO   BCKGRD METER/RANGE/PPM              .6/13/   1.       1.1/13/   1.       1.4/13/   1.       1.4/13/   1.
  CO2 SAMPLE METER/RANGE/PCT             83.5/13/  .18      59.3/12/  .24      65.1/11/  .55      72.9/13/  .15
  CO2 BCKGRD METER/RANGE/PCT             21.3/13/  .04      11.6/12/  .04       6.9/11/  .04      21.7/13/  .04
  NOX SAMPLE METER/RANGE/PPM             62.8/ 1/  19.      82.8/ 1/  25.      67.8/ 2/  68.      56.9/ 1/  17.
  NOX BCKGRD METER/RANGE/PPM              1.0/ 1/   0.        .9/ 1/   0.        .5/ 2/   1.       1.4/ 1/   0.

 .DILUTION FACTOR                          74.40              55.38              24.36              87.70
  HC   CONCENTRATION PPM                   14.                12.                15.                 9.
  CO   CONCENTRATION PPM                   23.                17.                15.                 8.
  CO2 CONCENTRATION PCT                    .14                .20                .51                .11
  NOX CONCENTRATION PPM                    18.4               24.4               67.3               16.5

  HC   MASS GRAMS                          3.58               3.28               4.04               2.29
  CO   MASS GRAMS                         12.28               9.14               8.12               4.52
  CO2 MASS GRAMS                         1150.4             1698.1             4394.7              930.6
  NOX MASS GRAMS                          16.13              21.66              60.83              14.58
  FUEL KG (LB)                         .374 (     .83)   .546 (    1.20)  1.402 (    3.09)   .300 (     .66)
  KW HR (HP HR)                        1.10 (    1.48)   1.89 (    2.53)   5.62 (    7.54)   1.10 (    1.47)

  BSHC G/KW HR (G/HP HR)               3.24 (    2.42)   1.74 (    1.30)    .72 (     .54)   2.09 (    1.56)
  BSCO G/KW HR (G/HP HR)              11.13 (    8.30)   4.84 (    3.61)   1.44 (    1.08)   4.12 (    3.07)
  BSCO2 G/KW HR (G/HP HR)           1042.41 (  777.33) 900.06 (  671.18) 781.61 (  582.85) 848.94 (  633.05)
  BSNOX G/KW HR (G/HP HR)             14.61 (   10.90)  11.48 (    8.56)  10.82 (    8.07)  13.30 (    9.92)
  BSFC KG/KW HR (LB/HP HR)             .339 (    .558)   .290 (    .476)   .249 (    .410)   .273 (    .449)

 TOTAL TEST RESULTS 4 BAGS                       PARTICULATE RESULTS, TOTAL FOR 4 BAGS

   TOTAL KW HR (HP HR)        9.71 ( 13.02)     90MM PARTICULATE RATES     GRAMS/TEST                 8.88
   BSHC  G/KW HR (G/HP HR)    1.36 (  1.01)                                G/KWHR(G/HPHR)          .91  (  .68)
   BSCO  G/KW HR (G/HP HR)    3.51 (  2.62)                                G/KG FUEL (G/LB FUEL)  3.39  ( 1.54)
   BSCO2 G/KW HR (G/HP HR)    842. (  628.)                                FILTER EFF.              93.4
   BSNOX G/KW HR (G/HP HR)   11.66 (  8.69)
   BSFC  KG/KW HR (LB/HP HR)  .270 (  .444)
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                         TABLE F-5. ENGINE EMISSION RESULTS (Cont'd)
                                       H-TRANS.                                  PROJECT NO. 03-7774-002

ENGINE  NO.                                  TEST NO.1      RUN2
ENGINE  MODEL     0 IHC DT466B               DATE  7/18/84
ENGINE  7.6 L(466. CID) L-6                  TIME                           DIESEL   EM-597-F
CVS NO.  11                                  DYNO NO.  1                    BAG CART NO.  1

BAROMETER 741.17 MM HG(29.18 IN HG)          RELATIVE HUMIDITY ,  ENGINE-65. PCT ,  CVS-65. PCT
DRY BULB TEMP. 22.2 DEG C(72.0 DEG F)        ABSOLUTE HUMIDITY 11.2 GM/KG( 78.3 GRAINS/LB)     NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                               1                  2                  3                  4
  DESCRIPTION                            NYNF               LANF                LAF               NYNF
  TIME SECONDS                           296.0              300.0              305.0              298.0
  TOT. BLOWER RATE SCMM (SCFM)       83.06 ( 2932.7)   83.03 ( 2931.8)   83.03 ( 2931.7)   83.00 ( 2930.8)
  TOT. 20X20 RATE SCMM (SCFM)         9.68 (341.8)      9.68 (341.8)      9.68 (341.8)      9.68 (341.8)
  TOT. 90MM RATE SCMM (SCFM)           .03 (  .89)       .03 (  .89)       .03 (  .89)       .03 (  .89)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)    .05 ( 1.74)       .05 ( 1.74)       .05 ( 1.74)       .05 ( 1.74)
  TOTAL FLOW STD. CU. METRES(SCF)    457.9 ( 16167.)   463.9 (16381.)    471.6 (16654.)    460.7 (16267.)

  HC  SAMPLE METER/RANGE/PPM         36.0/21/  18.     37.9/21/  19.     46.2/21/  23.     35.4/21/  18.
  HC  BCKGRD METER/RANGE/PPM         19.0/ 1/  10.     18.1/ 1/   9.     18.1/ 1/   9.     18.4/ 1/   9.
  CO  SAMPLE METER/RANGE/PPM         15.6/13/  14.     15.1/13/  14.     17.0/13/  15.     12.4/13/  11.
  CO  BCKGRD METER/RANGE/PPM           .9/13/   1.       .9/13/   1.      1.0/13/   1.      2.6/13/   2.
  CO2 SAMPLE METER/RANGE/PCT         72.3/13/  .15     57.2/12/  .23     63.7/11/  .53     74.2/13/  .15
  CO2 BCKGRD METER/RANGE/PCT         20.9/13/  .04     11.8/12/  .04      6.9/11/  .04     22.0/13/  .04
  NOX SAMPLE METER/RANGE/PPM         53.9/ 1/  16.     82.5/ 1/  25.     66.4/ 2/  66.     57.1/ 1/  17.
  NOX BCKGRD METER/RANGE/PPM          1.2/ 1/   0.      1.0/ 1/   0.       .3/ 2/   0.      1.2/ 1/   0.

  DILUTION FACTOR                         88.51              57.92              25.12              86.14
  HC  CONCENTRATION PPM                    9.                10.                14.                 9.
  CO  CONCENTRATION PPM                   13.                13.                14.                 9.
  CO2 CONCENTRATION PCT                     .11                .19                .49                .11
  NOX CONCENTRATION PPM                   15.7               24.3               66.1               16.6

  HC  MASS GRAMS                           2.27               2.69               3.92               2.28
  CO  MASS GRAMS                           6.94               6.78               7.75               4.66
  CO2 MASS GRAMS                         924.3             1603.8             4245.6              949.8
  NOX MASS GRAMS                          13.73              21.52              59.63              14.66
  FUEL KG (LB)                        .299 (    .66)    .515 (   1.13)   1.354 (   2.98)    .306 (    .67)
  KW HR (HP HR)                       1.10 (   1.48)    1.90 (   2.55)    5.64 (   7.56)    1.10 (   1.48)

  BSHC G/KW HR (G/HP HR)              2.05 (   1.53)    1.41 (   1.05)     .69 (    .52)    2.07 (   1.54)
  BSCO G/KW HR (G/HP HR)              6.29 (   4.69)    3.57 (   2.66)    1.37 (   1.02)    4.22 (   3.15)
  BSCO2 G/KW HR (G/HP HR)           837.54 ( 624.55)  843.41 ( 628.93)  753.11 ( 561.59)  860.64 ( 641.78)
  BSNOX G/KW HR (G/HP HR)            12.44 (   9.28)   11.31 (   8.44)   10.58 (   7.89)   13.28 (   9.90)
  BSFC KG/KW HR (LB/HP HR)            .271 (   .445)    .271 (   .445)    .240 (   .395)    .277 (   .455)

                                               PARTICULATE RESULTS, TOTAL FOR 4 BAGS
 TOTAL TEST RESULTS 4 BAGS
                                                                            GRAMS/TEST                 7.33
  TOTAL KW HR (HP HR)         9.75 ( 13.07)    90MM PARTICULATE RATES      G/KWHR(G/HPHR)           .75  (  .56)
  BSHC  G/KW HR (G/HP HR)     1.14 (   .85)                                G/KG FUEL (G/LB FUEL)   2.97  ( 1.34)
  BSCO  G/KW HR (G/HP HR)     2.68 (  2.00)                                FILTER EFF.                 93.8
  BSCO2 G/KW HR (G/HP HR)     792. (  591.)
  BSNOX G/KW HR (G/HP HR)    11.24 (  8.38)
  BSFC  KG/KW HR (LB/HP HR)   .254 (  .417)
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TABLE F-6. INDIVIDUAL HYDROCARBONS FROM COLD START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-597-F) DF-2

Individual HC from Test 5, Run 1, 7/17/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	400	41	150
Ethylene	860	89	320
Ethane	6.4	0.66	2.4
Acetylene	52	5.4	20
Propane	0	0	0
Propylene	610	63	230
Benzene	0	0	0
Toluene	0	0	0

Individual HC from Test 5, Run 2, 7/18/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	41	4.2	16
Ethylene	960	99	370
Ethane	1.5	0.15	0.57
Acetylene	77	7.9	29
Propane	0	0	0
Propylene	450	46	170
Benzene	0	0	0
Toluene	0	0	0

Average HC from Test 5, Runs 1 and 2

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	220	23	83
Ethylene	910	94	350
Ethane	4.0	0.41	1.5
Acetylene	65	6.7	25
Propane	0	0	0
Propylene	530	55	200
Benzene	0	0	0
Toluene	0	0	0

TABLE F-7. INDIVIDUAL HYDROCARBONS FROM HOT START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-597-F) DF-2

Individual HC from Test 5, Run 1, 7/17/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	62	6.4	25
Ethylene	730	75	290
Ethane	14	1.4	5.6
Acetylene	42	4.3	17
Propane	0	0	0
Propylene	70	7.2	28
Benzene	0	0	0
Toluene	0	0	0

Individual HC from Test 5, Run 2, 7/18/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	520	53	210
Ethylene	680	70	280
Ethane	3.5	0.36	1.4
Acetylene	49	5.1	20
Propane	0	0	0
Propylene	290	30	102
Benzene	77	7.0	3.2
Toluene	0	0	0

Average HC from Test 5, Runs 1 and 2

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	290	30	120
Ethylene	710	73	290
Ethane	8.8	0.88	3.5
Acetylene	46	4.7	19
Propane	0	0	0
Propylene	180	19	74
Benzene	39	4.0	1.6
Toluene	0	0	0

TABLE F-8. ALDEHYDES FROM COLD START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-597-F) DF-2

Aldehydes from Test 5, Run 1, 7/17/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1230	127	462
Acetaldehyde	417	43.2	157
Acrolein	246	25.5	92.5
Acetone	171	17.7	64.3
Propionaldehyde	93.2	9.65	35.0
Crotonaldehyde	61.1	6.33	23.0
Isobutyraldehyde & Methylethylketone	212	21.9	79.7
Benzaldehyde	60.8	6.29	22.9
Hexanaldehyde	58.8	6.09	22.1

Aldehydes from Test 5, Run 2, 7/18/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1099	113	419
Acetaldehyde	313	32.2	119
Acrolein	241	24.8	92.0
Acetone	207	21.3	79.0
Propionaldehyde	0	0	0
Crotonaldehyde	45.9	4.73	17.5
Isobutyraldehyde & Methylethylketone	259	26.7	98.9
Benzaldehyde	43.2	4.45	16.4
Hexanaldehyde	57.5	5.92	21.9

Average Aldehydes from Test 5, Runs 1 and 2

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1165	120	441
Acetaldehyde	365	37.7	138
Acrolein	244	25.2	92.3
Acetone	189	19.5	71.7
Propionaldehyde	46.6	4.83	17.5
Crotonaldehyde	53.5	5.53	20.3
Isobutyraldehyde & Methylethylketone	236	24.3	89.3
Benzaldehyde	52.0	5.37	19.7
Hexanaldehyde	58.2	6.01	22.0

TABLE F-9. ALDEHYDES FROM HOT START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-597-F) DF-2

Aldehydes from Test 5, Run 1, 7/17/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1095	113	442
Acetaldehyde	324	33.4	131
Acrolein	222	22.9	89.5
Acetone	214	22.1	86.3
Propionaldehyde	94.1	9.71	37.9
Crotonaldehyde	108	11.1	43.5
Isobutyraldehyde & Methylethylketone	293	30.2	118.1
Benzaldehyde	102	10.5	41.1
Hexanaldehyde	99	10.2	39.9

Aldehydes from Test 5, Run 2, 7/18/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	857	87.9	347
Acetaldehyde	179	18.4	72.5
Acrolein	38.5	3.9	15.6
Acetone	119	12.2	48.2
Propionaldehyde	0	0	0
Crotonaldehyde	30.3	3.11	12.3
Isobutyraldehyde & Methylethylketone	77.6	7.96	31.4
Benzaldehyde	43.9	4.50	17.8
Hexanaldehyde	38.8	3.98	15.7

Average Aldehydes from Test 5, Runs 1 and 2

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	976	100	395
Acetaldehyde	252	25.9	102
Acrolein	130	13.4	52.6
Acetone	167	17.2	67.3
Propionaldehyde	47.1	4.85	19.0
Crotonaldehyde	69.2	7.11	27.9
Isobutyraldehyde & Methylethylketone	185	19.1	74.8
Benzaldehyde	73.0	7.5	29.5
Hexanaldehyde	68.9	7.1	27.8

TABLE F-10. **FEDERAL SMOKE TEST TRACE EVALUATION**

Engine Model: IH DT466B **Test No.** 1 **Date:** 7-18-84

Engine S/N: Fuel: EM-597-F **Run No.** 1 **Eval. By:** K. Jack

Observed Power: 208 hp

Barometer 29.13

Accelerations

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	10.0	1	12.0	1	12.2
2	12.5	2	11.3	2	12.4
3	12.0	3	13.3	3	12.2
4	13.8	4	17.0	4	15.0
5	17.0	5	15.5	5	18.0
6	12.4	6	9.0	6	10.0
7	8.3	7	8.0	7	7.3
8	8.0	8	8.0	8	7.6
9	19.0	9	16.3	9	7.5
10	15.0	10	12.5	10	9.5
11	8.7	11	8.7	11	15.3
12	7.0	12	7.7	12	11.0
13	7.0	13	6.5	13	9.0
14	6.6	14	5.8	14	7.5
15	6.6	15	6.3	15	7.5

Total Smoke % 163.9 157.9 162.0

Factor (a) = $\frac{483.8}{45}$ = 10.8 %

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	6.2	1	5.5	1	5.8
2	5.9	2	5.7	2	5.8
3	6.3	3	5.8	3	5.8
4	6.0	4	5.3	4	6.2
5	6.0	5	5.7	5	5.8

Total Smoke % 30.4 28.0 29.4

Factor (b) = $\frac{87.8}{15}$ = 9.8 %

Peak

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	19.0	1	16.3	1	18.0
2	17.0	2	17.0	2	15.3
3	15.0	3	15.5	3	15.0

Total Smoke % 51.0 48.8 48.3

Factor (c) = $\frac{148.1}{9}$ = 16.5 %

F-14 Blank

909

APPENDIX G

RESULTS FROM OPERATION ON EM-599-F, HIGH NITROGEN HYDROCRACKER FEED (HNHF)

13-MODE FEDERAL DIESEL EMISSION CYCLE 1979

ENGINE: IHC DT466B H/C RATIO 1.99 BAROMETER: 29.17
TEST-2 FUEL: EM-599-F PROJECT: 03-7774-002 DATE: 7/19/84

MODE	POWER PCT	ENGINE SPEED COND / RPM	TORQUE OBS LB-FT	POWER OBS BHP	FUEL FLOW LB/MIN	AIR FLOW LB/MIN	INTAKE HUMID GR/LB	NOX CORR FACT	MEASURED HC PPM	MEASURED CO PPM	MEASURED CO2 PCT	MEASURED NOX PPM	CALCULATED GRAMS / HOUR HC	CALCULATED GRAMS / HOUR CO	CALCULATED GRAMS / HOUR NOX	MODE
1		IDLE / 685.	0.	.0	.038	5.43	80.	1.041	213.	224.	1.25	265.	17.	36.	73.	1
2	2	INTER / 1800.	10.	3.4	.130	15.58	80.	1.045	215.	202.	1.75	180.	43.	80.	121.	2
3	25	INTER / 1800.	118.	40.4	.285	16.38	80.	1.039	185.	202.	3.72	435.	40.	83.	304.	3
4	50	INTER / 1800.	237.	81.2	.508	17.95	80.	1.029	170.	104.	5.78	710.	43.	49.	567.	4
5	75	INTER / 1800.	365.	125.1	.738	20.68	73.	1.006	188.	125.	7.41	975.	55.	67.	863.	5
6	100	INTER / 1800.	450.	154.2	.895	22.45	73.	1.002	148.	247.	8.48	1100.	46.	141.	1027.	6
7		IDLE / 685.	0.	.0	.040	5.47	73.	1.021	253.	191.	1.17	260.	23.	34.	78.	7
8	100	RATED / 2600.	400.	198.0	1.322	37.19	73.	1.006	128.	433.	7.51	905.	66.	411.	1411.	8
9	75	RATED / 2600.	317.	156.9	.990	31.67	75.	1.013	138.	115.	6.61	830.	60.	93.	1113.	9
10	50	RATED / 2600.	212.	105.0	.697	27.56	75.	1.019	133.	93.	5.39	615.	49.	65.	715.	10
11	25	RATED / 2600.	106.	52.5	.455	24.12	75.	1.022	165.	136.	3.98	400.	53.	84.	411.	11
12	2	RATED / 2600.	9.	4.5	.262	21.47	75.	1.028	218.	158.	2.34	180.	67.	95.	181.	12
13		IDLE / 685.	0.	.0	.040	5.63	75.	1.023	268.	202.	1.25	235.	23.	34.	66.	13

MODE	CALCULATED GRAMS/LB-FUEL HC	CALCULATED GRAMS/LB-FUEL CO	CALCULATED GRAMS/LB-FUEL NOX	GRAMS/BHP-HR HC	GRAMS/BHP-HR CO	GRAMS/BHP-HR NOX	F/A DRY MEAS	F/A STOICH	"PHI"	WET HC CORR FACT	F/A CALC	F/A PCT MEAS	POWER CORR FACT	BSFC CORR LB/HP-HR	MODAL WEIGHT FACTOR	MODE
1	7.59	15.68	31.53	************		******	.0071	.0677	.105	.984	.0062	-12.7	.990	*****	.067	1
2	5.56	10.21	15.52	12.65	23.24	35.32	.0084	.0677	.125	.979	.0086	1.9	1.000	2.277	.080	2
3	2.32	4.87	17.78	.98	2.06	7.52	.0176	.0677	.260	.960	.0179	1.5	.999	.423	.080	3
4	1.41	1.62	18.60	.53	.61	6.99	.0286	.0677	.423	.942	.0273	-4.6	1.001	.375	.080	4
5	1.23	1.52	19.49	.44	.54	6.90	.0361	.0677	.533	.928	.0347	-3.7	1.005	.353	.080	5
6	.86	2.63	19.13	.30	.91	6.66	.0403	.0677	.595	.919	.0396	-1.8	1.008	.345	.080	6
7	9.58	14.25	32.32	************		******	.0074	.0677	.109	.986	.0058	-20.9	.989	*****	.067	7
8	.83	5.18	17.80	.33	2.08	7.13	.0359	.0677	.530	.927	.0353	-1.7	1.048	.382	.080	8
9	1.01	1.57	18.73	.38	.59	7.09	.0316	.0677	.466	.935	.0311	-1.6	1.033	.367	.080	9
10	1.18	1.56	17.11	.47	.62	6.82	.0256	.0677	.377	.946	.0255	-.1	1.020	.390	.080	10
11	1.95	3.07	15.07	1.01	1.60	7.84	.0191	.0677	.282	.958	.0190	-.2	1.014	.513	.080	11
12	4.27	6.02	11.50	15.04	21.21	40.53	.0123	.0677	.182	.974	.0114	-7.6	1.009	3.491	.080	12
13	9.52	14.11	27.39	************		******	.0072	.0677	.106	.985	.0062	-13.1	.991	*****	.067	13

CYCLE COMPOSITE USING 13-MODE WEIGHT FACTORS

BSHC ------- = .624 GRAM/BHP-HR
BSCO ------- = 1.363 GRAM/BHP-HR
BSNOX ------ = 7.485 GRAM/BHP-HR
BSHC + BSNOX = 8.109 GRAM/BHP-HR
CORR. BSFC - = .407 LBS/BHP-HR

TABLE G-2. SUPPLEMENTARY ENGINE DATA OBTAINED OVER 13-MODE TESTING ON (EM-599-F) HIGH NITROGEN HYDROCRACKER FEED

Test Mode No.	Fuel		Inlet Air			Exhaust		Oil	
	Temp.[a] °F	Press.[b] psi	Temp. °F	Restrict. in. H_2O	Boost psi	Temp. °F	B.P. in. H_2O	Temp. °F	Press. psi
1	93	28.0	80	1.1	0	310	0	200	21
2	94	48.5	79	5.3	0.5	344	0.20	195	48
3	94	48.0	78	5.8	1.4	485	0.25	197	48
4	93	47.0	77	6.9	3.6	675	0.35	200	47
5	93	45.5	76	8.8	7.0	855	0.55	204	46
6	95	44.5	76	10.2	9.9	968	0.80	210	44
7	94	28.0	79	1.2	0	333	0	207	20
8	91	55.5	76	24.8	15.8	975	2.2	211	49
9	93	56.0	77	18.7	11.3	865	1.5	222	47
10	96	57.5	77	14.2	7.0	743	1.0	221	48
11	96	59.0	78	10.9	3.8	614	0.70	218	48
12	97	60.5	78	9.2	1.8	451	0.50	214	49
13	97	28.0	80	1.1	0	194	0	204	20

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[a] Measured at inlet to pump

[b] Measured after secondary filter

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                         TABLE G-3.  ENGINE EMISSION RESULTS
                                          C-TRANS.                              PROJECT NO. 03-7774-002

ENGINE  NO.                                   TEST NO.2       RUN1
ENGINE  MODEL     0 IHC DT466B                DATE  7/19/84
ENGINE  7.6 L(466. CID) L-6                   TIME                             DIESEL    EM-599-F
CVS NO.  11                                   DYNO NO.  1                      BAG CART NO.  1

BAROMETER 742.19 MM HG(29.22 IN HG)           RELATIVE HUMIDITY ,  ENGINE-65. PCT ,  CVS-65. PCT
DRY BULB TEMP. 22.8 DEG C(73.0 DEG F)         ABSOLUTE HUMIDITY 11.6 GM/KG( 81.5 GRAINS/LB)      NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                       1                  2                  3                  4
  DESCRIPTION                                    NYNF               LANF                LAF               NYNF
  TIME SECONDS                                   296.0              300.0              305.0              298.0
  TOT. BLOWER RATE SCMM (SCFM)             83.18 ( 2937.1)   83.15 ( 2936.2)   83.18 ( 2937.1)   83.16 ( 2936.3)
  TOT. 20X20 RATE SCMM (SCFM)               9.76 (344.7)      9.76 (344.7)      9.76 (344.7)      9.76 (344.7)
  TOT. 90MM RATE SCMM (SCFM)                 .03 (  .90)       .03 (  .90)       .03 (  .90)       .03 (  .90)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)          .05 ( 1.74)       .05 ( 1.74)       .05 ( 1.74)       .05 ( 1.74)
  TOTAL FLOW STD. CU. METRES(SCF)          458.9 (  16203.)  465.0 (16417.)    472.8 (16696.)    461.9 (16309.)

  HC  SAMPLE METER/RANGE/PPM               31.8/21/  16.     33.8/21/  17.     44.1/21/  22.     31.6/21/  16.
  HC  BCKGRD METER/RANGE/PPM               16.0/ 1/   8.     17.0/ 1/   9.     19.0/ 1/  10.     20.2/ 1/  10.
  CO  SAMPLE METER/RANGE/PPM               17.6/13/  16.     16.1/13/  15.     19.5/13/  18.      9.3/13/   8.
  CO  BCKGRD METER/RANGE/PPM                1.0/13/   1.      1.4/13/   1.      1.6/13/   1.      1.7/13/   2.
  CO2 SAMPLE METER/RANGE/PCT               44.9/12/  .17     58.1/12/  .23     64.6/11/  .54     72.6/13/  .15
  CO2 BCKGRD METER/RANGE/PCT               12.0/12/  .04     12.0/12/  .04      7.2/11/  .04     22.2/13/  .04
  NOX SAMPLE METER/RANGE/PPM               55.7/ 1/  17.     73.4/ 1/  22.     60.9/ 2/  61.     49.6/ 1/  15.
  NOX BCKGRD METER/RANGE/PPM                 .8/ 1/   0.      1.1/ 1/   0.       .5/ 2/   1.      1.2/ 1/   0.

  DILUTION FACTOR                               76.57              56.89              24.63              88.55
  HC  CONCENTRATION PPM                          8.                 9.                13.                 6.
  CO  CONCENTRATION PPM                         15.                13.                16.                 7.
  CO2 CONCENTRATION PCT                           .13                .19                .50                .11
  NOX CONCENTRATION PPM                         16.3               21.5               60.4               14.4

  HC  MASS GRAMS                                 2.11               2.30               3.53               1.54
  CO  MASS GRAMS                                 7.87               7.05               8.71               3.61
  CO2 MASS GRAMS                              1106.3             1638.0             4332.0              916.9
  NOX MASS GRAMS                                14.34              19.13              54.63              12.72
  FUEL KG (LB)                               .359 (    .79)    .529 (   1.17)   1.391 (   3.07)    .296 (    .65)
  KW HR (HP HR)                              1.07 (   1.44)    1.87 (   2.51)    5.62 (   7.53)    1.07 (   1.44)

  BSHC G/KW HR (G/HP HR)                     1.97 (   1.47)    1.23 (    .92)     .63 (    .47)    1.44 (   1.07)
  BSCO G/KW HR (G/HP HR)                     7.33 (   5.46)    3.77 (   2.81)    1.55 (   1.16)    3.36 (   2.51)
  BSCO2 G/KW HR (G/HP HR)                 1030.23 ( 768.24)  875.11 ( 652.57)  771.48 ( 575.29)  853.85 ( 636.71)
  BSNOX G/KW HR (G/HP HR)                   13.35 (   9.95)   10.22 (   7.62)    9.73 (   7.26)   11.85 (   8.83)
  BSFC KG/KW HR (LB/HP HR)                   .335 (   .550)    .283 (   .464)    .248 (   .407)    .276 (   .453)

TOTAL TEST RESULTS 4 BAGS                            PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)          9.63 ( 12.92)        90MM PARTICULATE RATES    GRAMS/TEST                 6.22
  BSHC   G/KW HR (G/HP HR)      .98 (   .73)                                  G/KWHR(G/HPHR)             .65  (  .48)
  BSCO   G/KW HR (G/HP HR)     2.83 (  2.11)                                  G/KG FUEL (G/LB FUEL)     2.42  ( 1.10)
  BSCO2  G/KW HR (G/HP HR)     830. (  619.)                                  FILTER EFF.                 92.0
  BSNOX  G/KW HR (G/HP HR)    10.46 (  7.80)
  BSFC   KG/KW HR (LB/HP HR)   .267 (  .439)
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                              TABLE G-3.  ENGINE EMISSION RESULTS  (Cont'd)
                                               H-TRANS.                                      PROJECT NO. 03-7774-002

ENGINE  NO.                                         TEST NO.2      RUN1
ENGINE  MODEL    0 IHC DT466B                       DATE  7/19/84
ENGINE  7.6 L(466. CID) L-6                         TIME                             DIESEL    EM-599-F
CVS NO.  11                                         DYNO NO.  1                      BAG CART NO.  1

BAROMETER 742.44 MM HG(29.23 IN HG)                 RELATIVE HUMIDITY ,  ENGINE-65. PCT ,  CVS-66. PCT
DRY BULB TEMP. 22.2 DEG C(72.0 DEG F)               ABSOLUTE HUMIDITY 11.2 GM/KG( 78.2 GRAINS/LB)     NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                    1                  2                  3                  4
  DESCRIPTION                                 NYNF               LANF                LAF               NYNF
  TIME SECONDS                               296.0              300.0              305.0              298.0
  TOT. BLOWER RATE SCMM (SCFM)          83.31 ( 2941.6)    83.31 ( 2941.8)    83.32 ( 2942.0)    83.31 ( 2941.5)
  TOT. 20X20 RATE SCMM (SCFM)            9.74 (343.8)       9.74 (343.8)       9.74 (343.8)       9.74 (343.8)
  TOT. 90MM RATE SCMM (SCFM)              .03 (  .90)        .03 (  .90)        .03 (  .90)        .03 (  .90)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)       .05 ( 1.75)        .05 ( 1.75)        .05 ( 1.75)        .05 ( 1.75)
  TOTAL FLOW STD. CU. METRES(SCF)       459.4 (  16221.)   465.6 (16441.)     473.4 (16716.)     462.5 (16330.)

  HC  SAMPLE METER/RANGE/PPM            29.6/21/  15.      34.3/21/  17.      41.9/21/  21.      32.7/21/  16.
  HC  BCKGRD METER/RANGE/PPM            18.0/ 1/   9.      18.8/ 1/   9.      18.7/ 1/   9.      18.9/ 1/   9.
  CO  SAMPLE METER/RANGE/PPM            10.7/13/  10.      11.6/13/  10.      18.1/13/  16.       9.0/13/   8.
  CO  BCKGRD METER/RANGE/PPM             1.5/13/   1.       1.0/13/   1.       1.4/13/   1.       1.4/13/   1.
  CO2 SAMPLE METER/RANGE/PCT            69.5/13/  .14      99.9/13/  .22      62.3/11/  .51      71.1/13/  .15
  CO2 BCKGRD METER/RANGE/PCT            22.4/13/  .04      22.7/13/  .04       7.3/11/  .04      22.3/13/  .04
  NOX SAMPLE METER/RANGE/PPM            44.4/ 1/  13.      69.4/ 1/  21.      56.5/ 2/  57.      45.8/ 1/  14.
  NOX BCKGRD METER/RANGE/PPM             1.1/ 1/   0.       1.3/ 1/   0.        .5/ 2/   1.       1.3/ 1/   0.

  DILUTION FACTOR                          92.97              59.36              25.90              90.64
  HC  CONCENTRATION PPM                       6.                 8.                12.                 7.
  CO  CONCENTRATION PPM                       8.                 9.                15.                 7.
  CO2 CONCENTRATION PCT                      .10                .18                .47                .10
  NOX CONCENTRATION PPM                     12.9               20.3               56.0               13.2

  HC  MASS GRAMS                            1.57               2.12               3.27               1.86
  CO  MASS GRAMS                            4.35               5.07               8.13               3.61
  CO2 MASS GRAMS                           847.9             1549.5             4102.0              886.7
  NOX MASS GRAMS                           11.32              18.05              50.72              11.71
  FUEL KG (LB)                          .274 (    .61)    .499 (   1.10)   1.317 (   2.90)    .287 (    .63)
  KW HR (HP HR)                         1.10 (   1.47)    1.87 (   2.51)    5.62 (   7.53)    1.07 (   1.44)

  BSHC G/KW HR (G/HP HR)                1.43 (   1.07)    1.13 (    .84)     .58 (    .43)    1.74 (   1.29)
  BSCO G/KW HR (G/HP HR)                3.97 (   2.96)    2.71 (   2.02)    1.45 (   1.08)    3.37 (   2.51)
  BSCO2 G/KW HR (G/HP HR)             773.46 ( 576.77)  827.88 ( 617.35)  730.53 ( 544.75)  825.72 ( 615.74)
  BSNOX G/KW HR (G/HP HR)              10.33 (   7.70)    9.64 (   7.19)    9.03 (   6.74)   10.91 (   8.13)
  BSFC KG/KW HR (LB/HP HR)              .250 (   .412)    .267 (   .439)    .235 (   .386)    .267 (   .439)

TOTAL TEST RESULTS 4 BAGS                               PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)          9.66 ( 12.95)        90MM PARTICULATE RATES      GRAMS/TEST                 5.31
  BSHC  G/KW HR (G/HP HR)       .91 (   .68)                                    G/KWHR(G/HPHR)          .55  (  .41)
  BSCO  G/KW HR (G/HP HR)      2.19 (  1.63)                                    G/KG FUEL (G/LB FUEL)  2.23  ( 1.01)
  BSCO2 G/KW HR (G/HP HR)      765. (  570.)                                    FILTER EFF.              93.4
  BSNOX G/KW HR (G/HP HR)      9.51 (  7.09)
  BSFC  KG/KW HR (LB/HP HR)    .246 (  .405)
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                                        TABLE G-4. ENGINE EMISSION RESULTS
                                                   C-TRANS.
                                                                                         PROJECT NO. 03-7774-002
ENGINE  NO.
ENGINE  MODEL     0 IHC DT466B              TEST NO.2      RUN2
ENGINE  7.6 L(466. CID) L-6                 DATE  7/20/84
CVS NO.  11                                 TIME
                                                                               DIESEL    EM-599-F
                                            DYNO NO.  1                        BAG CART NO.  1
BAROMETER 741.17 MM HG(29.18 IN HG)
DRY BULB TEMP. 22.8 DEG C(73.0 DEG F)      RELATIVE HUMIDITY ,  ENGINE-65. PCT ,  CVS-65. PCT
                                            ABSOLUTE HUMIDITY 11.7 GM/KG( 81.6 GRAINS/LB)      NOX HUMIDITY C.F. 1.0000
BAG RESULTS
  BAG NUMBER                                      1                    2                    3                    4
  DESCRIPTION                                   NYNF                 LANF                  LAF                 NYNF
  TIME SECONDS                                  296.0                300.0                305.0                298.0
  TOT. BLOWER RATE SCMM (SCFM)            83.15 ( 2936.2)      83.15 ( 2935.9)      83.16 ( 2936.2)      83.16 ( 2936.4)
  TOT. 20X20 RATE SCMM (SCFM)              9.74 (344.0)         9.74 (344.0)         9.74 (344.0)         9.74 (344.0)
  TOT. 90MM RATE SCMM (SCFM)                .03 (   .90)         .03 (   .90)         .03 (   .90)         .03 (   .90)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)         .05 ( 1.71)          .05 ( 1.71)          .05 ( 1.71)          .05 ( 1.71)
  TOTAL FLOW STD. CU. METRES(SCF)         458.7 (  16195.)     464.8 (16413.)       472.6 (16688.)       461.8 (16306.)

  HC   SAMPLE METER/RANGE/PPM             31.8/21/  16.        31.2/21/  16.        40.7/21/  20.        31.7/21/  16.
  HC   BCKGRD METER/RANGE/PPM             19.0/ 1/  10.        17.5/ 1/   9.        18.0/ 1/   9.        18.8/ 1/   9.
  CO   SAMPLE METER/RANGE/PPM             17.8/13/  16.        16.3/13/  15.        18.8/13/  17.         9.2/13/   8.
  CO   BCKGRD METER/RANGE/PPM               .7/13/   1.         1.4/13/   1.         1.5/13/   1.         1.1/13/   1.
  CO2  SAMPLE METER/RANGE/PCT             81.1/13/  .17        58.7/12/  .24        64.4/11/  .54        71.4/13/  .15
  CO2  BCKGRD METER/RANGE/PCT             22.4/13/  .04        12.4/12/  .04         7.2/11/  .04        21.8/13/  .04
  NOX  SAMPLE METER/RANGE/PPM             55.5/ 1/  17.        73.8/ 1/  22.        61.5/ 2/  62.        47.1/ 1/  14.
  NOX  BCKGRD METER/RANGE/PPM               .7/ 1/   0.          .9/ 1/   0.          .4/ 2/   0.          .9/ 1/   0.

  DILUTION FACTOR                               77.58                56.24                24.74                90.23
  HC   CONCENTRATION PPM                         7.                   7.                  12.                   7.
  CO   CONCENTRATION PPM                        15.                  13.                  15.                   7.
  CO2  CONCENTRATION PCT                         .13                  .19                  .50                  .11
  NOX  CONCENTRATION PPM                        16.3                 21.7                 61.1                 13.7

  HC   MASS GRAMS                                1.72                 1.88                 3.20                 1.75
  CO   MASS GRAMS                                8.10                 7.14                 8.41                 3.85
  CO2  MASS GRAMS                             1081.0               1650.1               4309.7                899.5
  NOX  MASS GRAMS                               14.30                19.28                55.24                12.14
  FUEL KG (LB)                             .351 (     .77)    .532 (    1.17)    1.383 (    3.05)     .291 (     .64)
  KW HR (HP HR)                            1.08 (    1.45)    1.87 (    2.51)     5.62 (    7.53)     1.07 (    1.44)

  BSHC G/KW HR (G/HP HR)                   1.59 (    1.19)    1.00 (     .75)      .57 (     .42)     1.63 (    1.21)
  BSCO G/KW HR (G/HP HR)                   7.49 (    5.59)    3.82 (    2.85)     1.50 (    1.12)     3.58 (    2.67)
  BSCO2 G/KW HR (G/HP HR)                999.73 ( 745.50)   881.59 ( 657.40)   767.51 ( 572.33)   837.71 ( 624.68)
  BSNOX G/KW HR (G/HP HR)                 13.23 (    9.86)   10.30 (    7.68)     9.84 (    7.34)    11.31 (    8.43)
  BSFC KG/KW HR (LB/HP HR)                 .325 (    .534)    .284 (    .468)     .246 (    .405)     .271 (    .445)

TOTAL TEST RESULTS 4 BAGS                             PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)            9.64 ( 12.93)      90MM PARTICULATE RATES    GRAMS/TEST                    6.10
  BSHC  G/KW HR (G/HP HR)         .89 (   .66)                                G/KWHR(G/HPHR)             .63  (  .47)
  BSCO  G/KW HR (G/HP HR)        2.85 (  2.13)                                G/KG FUEL (G/LB FUEL)     2.39  ( 1.08)
  BSCO2 G/KW HR (G/HP HR)        824. (  614.)                                FILTER EFF.                  93.5
  BSNOX G/KW HR (G/HP HR)       10.47 (  7.81)
  BSFC  KG/KW HR (LB/HP HR)      .265 (  .436)
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TABLE G-4. ENGINE EMISSION RESULTS (Cont'd)

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                                              H-TRANS.                                          PROJECT NO. 03-7774-002

ENGINE  NO.                                   TEST NO.2      RUN2
ENGINE  MODEL     0 IHC DT466B                DATE  7/20/84
ENGINE  7.6 L(466. CID) L-6                   TIME                           DIESEL    EM-599-F
CVS NO.  11                                   DYNO NO.  1                    BAG CART NO.  1

BAROMETER 740.92 MM HG(29.17 IN HG)           RELATIVE HUMIDITY ,  ENGINE-58. PCT ,  CVS-58. PCT
DRY BULB TEMP. 23.3 DEG C(74.0 DEG F)         ABSOLUTE HUMIDITY 10.7 GM/KG( 75.0 GRAINS/LB)       NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                         1                   2                   3                   4
  DESCRIPTION                                      NYNF                LANF                 LAF                NYNF
  TIME SECONDS                                    296.0               300.0               305.0               298.0
  TOT. BLOWER RATE SCMM (SCFM)             83.09 ( 2934.0)     83.11 ( 2934.5)     83.11 ( 2934.4)     83.12 ( 2935.0)
  TOT. 20X20 RATE SCMM (SCFM)               9.72 (343.1)        9.72 (343.1)        9.72 (343.1)        9.72 (343.1)
  TOT. 90MM RATE SCMM (SCFM)                 .03 (   .89)        .03 (   .89)        .03 (   .89)        .03 (   .89)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)          .05 ( 1.71)         .05 ( 1.71)         .05 ( 1.71)         .05 ( 1.71)
  TOTAL FLOW STD. CU. METRES(SCF)          458.2 (  16180.)    464.5 (16401.)      472.2 (16674.)      461.5 (16294.)

  HC   SAMPLE METER/RANGE/PPM              29.2/21/  15.       33.0/21/  16.       40.8/21/  20.       32.6/21/  16.
  HC   BCKGRD METER/RANGE/PPM              19.0/ 1/  10.       17.5/ 1/   9.       18.0/ 1/   9.       18.8/ 1/   9.
  CO   SAMPLE METER/RANGE/PPM              11.3/13/  10.       13.2/13/  12.       17.8/13/  16.        8.1/13/   7.
  CO   BCKGRD METER/RANGE/PPM                .5/13/   0.         .7/13/   1.         .8/13/   1.         .1/13/   0.
  CO2 SAMPLE METER/RANGE/PCT               66.9/13/  .14       56.1/12/  .22       62.6/11/  .52       69.7/13/  .14
  CO2 BCKGRD METER/RANGE/PCT               21.6/13/  .04       12.2/12/  .04        7.0/11/  .04       21.6/13/  .04
  NOX SAMPLE METER/RANGE/PPM               42.3/ 1/  13.       70.3/ 1/  21.       56.9/ 2/  57.       45.5/ 1/  14.
  NOX BCKGRD METER/RANGE/PPM                 .9/ 1/   0.        1.2/ 1/   0.         .5/ 2/   1.        1.5/ 1/   0.

  DILUTION FACTOR                                96.94               59.36               25.73               92.72
  HC   CONCENTRATION PPM                            5.                  8.                 12.                  7.
  CO   CONCENTRATION PPM                           10.                 11.                 15.                  7.
  CO2 CONCENTRATION PCT                            .10                 .18                 .48                 .10
  NOX CONCENTRATION PPM                           12.3                20.6                56.4                13.1

  HC   MASS GRAMS                                 1.38                2.11                3.20                1.87
  CO   MASS GRAMS                                 5.10                5.98                8.26                3.80
  CO2 MASS GRAMS                                 808.8              1549.4              4136.4               868.8
  NOX MASS GRAMS                                 10.80               18.27               50.95               11.56
  FUEL KG (LB)                              .262 (     .58)     .500 (    1.10)    1.328 (    2.93)     .281 (     .62)
  KW HR (HP HR)                             1.08 (    1.45)     1.87 (    2.51)     5.63 (    7.55)     1.07 (    1.43)

  BSHC G/KW HR (G/HP HR)                    1.27 (     .95)     1.13 (     .84)      .57 (     .42)     1.75 (    1.30)
  BSCO G/KW HR (G/HP HR)                    4.72 (    3.52)     3.20 (    2.38)     1.47 (    1.09)     3.56 (    2.65)
  BSCO2 G/KW HR (G/HP HR)                 748.05 (  557.82)   827.82 (  617.31)   734.70 (  547.86)   814.76 (  607.57)
  BSNOX G/KW HR (G/HP HR)                   9.98 (    7.44)     9.76 (    7.28)     9.05 (    6.75)    10.84 (    8.08)
  BSFC KG/KW HR (LB/HP HR)                  .242 (    .399)     .267 (    .439)     .236 (    .388)     .264 (    .433)

TOTAL TEST RESULTS 4 BAGS                              PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)          9.65 ( 12.94)           90MM PARTICULATE RATES     GRAMS/TEST                   5.61
  BSHC   G/KW HR (G/HP HR)      .89 (   .66)                                      G/KWHR(G/HPHR)            .58  (  .43)
  BSCO   G/KW HR (G/HP HR)     2.40 (  1.79)                                      G/KG FUEL (G/LB FUEL)    2.37  ( 1.07)
  BSCO2  G/KW HR (G/HP HR)     763. (  569.)                                      FILTER EFF.                  93.9
  BSNOX  G/KW HR (G/HP HR)     9.49 (  7.08)
  BSFC   KG/KW HR (LB/HP HR)   .246 (  .404)
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TABLE G-5. INDIVIDUAL HYDROCARBONS FROM COLD START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-599-F) HNHF

Individual HC from Test 6, Run 1, 7/19/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	340	35	130
Ethylene	850	88	330
Ethane	15	1.6	5.8
Acetylene	48	5.0	19
Propane	0	0	0
Propylene	220	23	85
Benzene	0	0	0
Toluene	0	0	0

Individual HC from Test 6, Run 2, 7/20/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	400	41	160
Ethylene	810	84	320
Ethane	0	0	0
Acetylene	38	3.9	15
Propane	0	0	0
Propylene	260	27	100
Benzene	0	0	0
Toluene	0	0	0

Average HC from Test 6, Runs 1 and 2

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	370	38	150
Ethylene	830	86	330
Ethane	7.5	0.80	2.9
Acetylene	43	4.5	17
Propane	0	0	0
Propylene	240	25	93
Benzene	0	0	0
Toluene	0	0	0

TABLE G-6. INDIVIDUAL HYDROCARBONS FROM HOT START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-599-F) HNHF

Individual HC from Test 6, Run 1, 7/19/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	0	0	0
Ethylene	710	73	300
Ethane	0	0	0
Acetylene	0	0	0
Propane	0	0	0
Propylene	210	22	88
Benzene	0	0	0
Toluene	0	0	0

Individual HC from Test 6, Run 2, 7/20/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	0	0	0
Ethylene	700	73	300
Ethane	0	0	0
Acetylene	39	4.0	16
Propane	0	0	0
Propylene	240	25	100
Benzene	140	15	59
Toluene	0	0	0

Average HC from Test 6, Runs 1 and 2

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	0	0	0
Ethylene	710	73	300
Ethane	0	0	0
Acetylene	20	2.0	8.0
Propane	0	0	0
Propylene	230	24	94
Benzene	700	7.5	30
Toluene	0	0	0

TABLE G-7. ALDEHYDES FROM COLD START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-599-F) HNHF

Aldehydes from Test 6, Run 1, 7/19/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	631	65.5	245
Acetaldehyde	184	19.1	71.3
Acrolein	72.8	7.56	28.2
Acetone	236.1	24.5	91.5
Propionaldehyde	0	0	0
Crotonaldehyde	45.6	4.74	17.7
Isobutyraldehyde & Methylethylketone	108	11.2	41.9
Benzaldehyde	0	0	0
Hexanaldehyde	58.3	6.1	22.6

Aldehydes from Test 6, Run 2, 7/20/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	783	81.2	306
Acetaldehyde	292	30.3	114
Acrolein	31.1	3.23	12.1
Acetone	250.2	26.0	97.7
Propionaldehyde	0	0	0
Crotonaldehyde	43.8	4.54	17.1
Isobutyraldehyde & Methylethylketone	136.8	14.2	53.4
Benzaldehyde	59.2	6.14	23.1
Hexanaldehyde	38.2	3.96	14.9

Average Aldehydes from Test 6, Runs 1 and 2

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	707	73.4	276
Acetaldehyde	238	24.7	92.7
Acrolein	52.0	5.40	20.2
Acetone	243	25.3	94.6
Propionaldehyde	0	0	0
Crotonaldehyde	44.7	4.64	17.4
Isobutyraldehyde & Methylethylketone	122	12.7	47.7
Benzaldehyde	29.6	3.07	11.6
Hexanaldehyde	48.3	5.03	18.8

TABLE G-8. ALDEHYDES FROM HOT START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-599-F) HNHF

Aldehydes from Test 6, Run 1, 7/19/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	601	62.2	253
Acetaldehyde	0	0	0
Acrolein	35.6	3.69	15.0
Acetone	172.6	17.9	72.5
Propionaldehyde	0	0	0
Crotonaldehyde	15.4	1.59	6.47
Isobutyraldehyde & Methylethylketone	78.4	8.12	33.9
Benzaldehyde	61.1	6.33	25.7
Hexanaldehyde	78.8	8.16	33.1

Aldehydes from Test 6, Run 2, 7/20/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	473	49.0	200
Acetaldehyde	157	16.3	66.2
Acrolein	120	12.4	50.6
Acetone	182	18.9	76.8
Propionaldehyde	0	0	0
Crotonaldehyde	0	0	0
Isobutyraldehyde & Methylethylketone	45.7	4.74	19.3
Benzaldehyde	19.8	2.05	8.35
Hexanaldehyde	57.4	5.95	24.2

Average Aldehydes from Test 6, Runs 1 and 2

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	537	55.6	227
Acetaldehyde	78.5	8.15	33.1
Acrolein	77.8	8.05	32.8
Acetone	177.3	18.4	74.7
Propionaldehyde	0	0	0
Crotonaldehyde	7.70	0.80	3.24
Isobutyraldehyde & Methylethylketone	62.1	6.43	26.6
Benzaldehyde	40.5	4.19	17.0
Hexanaldehyde	68.1	7.06	28.7

TABLE G-9. FEDERAL SMOKE TEST TRACE EVALUATION

Engine Model: IH DT-466B Test No. 2 Date: 7-20-84

Engine S/N: Fuel: EM-599-F Run No. 1 Eval. By: K. Jack

Accelerations Observed Power: 197 hp Barometer: 29.12

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	9.0	1	11.5	1	5.2
2	13.0	2	15.5	2	10.0
3	9.7	3	13.5	3	9.4
4	9.3	4	10.5	4	8.7
5	9.0	5	9.0	5	8.0
6	13.4	6	15.5	6	14.5
7	6.4	7	9.0	7	9.5
8	5.0	8	7.0	8	6.3
9	5.5	9	6.2	9	6.0
10	9.5	10	13.0	10	6.0
11	8.5	11	13.0	11	9.0
12	6.5	12	10.8	12	9.5
13	5.3	13	4.8	13	6.3
14	5.2	14	5.2	14	5.3
15	5.1	15	6.0	15	5.2

Total Smoke % 120.4 150.5 118.9

Factor (a) = $\frac{389.8}{45}$ = 8.7 %

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	3.5	1	3.5	1	3.8
2	3.3	2	3.5	2	3.8
3	3.4	3	3 3	3	3.9
4	4.2	4	3.8	4	4.0
5	3.8	5	3.6	5	4.6

Total Smoke % 18.2 17.7 20.1

Factor (b) = $\frac{56.0}{15}$ = 3.7 %

Peak

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	13.4	1	15.5	1	14.5
2	13.0	2	15.5	2	10.0
3	9.7	3	13.5	3	9.5

Total Smoke % 36.1 44.5 34.0

Factor (c) = $\frac{114.6}{9}$ = 12.7 %

APPENDIX H

RESULTS FROM OPERATION ON EM-600-F, DISTILLATE

TABLE H-1. 13-MODE FEDERAL DIESEL EMISSION CYCLE 1979

ENGINE: IHC DT466B H/C RATIO 1.76 BAROMETER: 29.21
TEST-7 FUEL: EM-600-F PROJECT: 03-7774-002 DATE: 7/24/84

MODE	POWER PCT	ENGINE SPEED COND / RPM	TORQUE OBS LB-FT	POWER OBS BHP	FUEL FLOW LB/MIN	AIR FLOW LB/MIN	INTAKE HUMID GR/LB	NOX CORR FACT	MEASURED HC PPM	MEASURED CO PPM	MEASURED CO2 PCT	MEASURED NOX PPM	CALCULATED GRAMS / HOUR HC	CALCULATED GRAMS / HOUR CO	CALCULATED GRAMS / HOUR NOX	MODE
1		IDLE / 690.	0.	.0	.043	5.61	65.	.997	325.	517.	1.21	270.	30.	96.	81.	1
2	2	INTER / 1800.	10.	3.4	.148	15.95	65.	1.000	335.	554.	1.89	275.	70.	229.	186.	2
3	25	INTER / 1800.	118.	40.4	.318	16.52	65.	.998	228.	338.	3.98	410.	51.	147.	291.	3
4	50	INTER / 1800.	237.	81.2	.525	18.11	68.	1.002	185.	136.	6.11	925.	45.	64.	715.	4
5	75	INTER / 1800.	365.	125.1	.768	20.86	68.	.994	188.	125.	7.89	1200.	53.	67.	1044.	5
6	100	INTER / 1800.	471.	161.4	.960	22.65	68.	.990	168.	409.	9.21	1325.	51.	234.	1226.	6
7		IDLE / 690.	0.	.0	.035	5.75	70.	1.010	380.	505.	1.21	265.	28.	75.	65.	7
8	100	RATED / 2600.	415.	205.4	1.420	38.01	75.	1.008	118.	350.	7.89	1100.	62.	346.	1790.	8
9	75	RATED / 2600.	317.	156.9	1.060	33.68	75.	1.013	138.	83.	6.78	975.	62.	71.	1388.	9
10	50	RATED / 2600.	212.	105.0	.758	29.59	75.	1.019	130.	62.	5.62	725.	50.	46.	896.	10
11	25	RATED / 2600.	106.	52.5	.508	25.10	72.	1.011	158.	136.	4.17	505.	54.	91.	557.	11
12	2	RATED / 2600.	9.	4.5	.283	22.90	72.	1.020	273.	327.	2.50	260.	84.	200.	265.	12
13		IDLE / 690.	0.	.0	.038	5.76	72.	1.020	405.	445.	1.34	285.	30.	66.	71.	13

MODE	CALCULATED GRAMS/LB-FUEL HC	CALCULATED GRAMS/LB-FUEL CO	CALCULATED GRAMS/LB-FUEL NOX	CALCULATED GRAMS/BHP-HR HC	CALCULATED GRAMS/BHP-HR CO	CALCULATED GRAMS/BHP-HR NOX	F/A DRY MEAS	F/A STOICH	"PHI"	WET HC CORR FACT	F/A CALC	F/A PCT MEAS	POWER CORR FACT	BSFC CORR LB/HP-HR	MODAL WEIGHT FACTOR	MODE
1	11.54	36.79	31.25	************		******	.0078	.0693	.113	.987	.0061	-21.3	.986	*****	.067	1
2	7.83	25.78	20.89	20.33	66.96	54.25	.0094	.0693	.136	.980	.0093	-.4	.995	2.611	.080	2
3	2.66	7.71	15.24	1.26	3.64	7.20	.0194	.0693	.281	.963	.0189	-2.9	.995	.475	.080	3
4	1.44	2.04	22.68	.56	.79	8.80	.0293	.0693	.423	.946	.0285	-2.7	.996	.389	.080	4
5	1.15	1.45	22.64	.43	.54	8.34	.0372	.0693	.537	.932	.0364	-2.0	1.002	.368	.080	5
6	.89	4.07	21.28	.32	1.45	7.59	.0428	.0693	.618	.922	.0424	-.9	1.005	.355	.080	6
7	13.46	35.82	30.97	************		******	.0061	.0693	.089	.986	.0062	.1	.987	*****	.067	7
8	.72	4.06	21.01	.30	1.68	8.71	.0378	.0693	.545	.932	.0365	-3.3	1.048	.396	.080	8
9	.98	1.12	21.83	.40	.46	8.85	.0318	.0693	.459	.940	.0314	-1.1	1.034	.392	.080	9
10	1.10	1.01	19.69	.48	.44	8.53	.0259	.0693	.374	.949	.0262	1.1	1.024	.424	.080	10
11	1.77	2.98	18.27	1.03	1.73	10.62	.0205	.0693	.295	.961	.0196	-4.0	1.015	.573	.080	11
12	4.96	11.77	15.57	18.92	44.89	59.42	.0125	.0693	.180	.975	.0121	-3.5	1.008	3.783	.080	12
13	13.09	28.76	30.66	************		******	.0067	.0693	.097	.985	.0067	.4	.988	*****	.067	13

CYCLE COMPOSITE USING 13-MODE WEIGHT FACTORS

BSHC ------- = .702 GRAM/BHP-HR
BSCO ------- = 1.812 GRAM/BHP-HR
BSNOX ------ = 9.123 GRAM/BHP-HR
BSHC + BSNOX = 9.825 GRAM/BHP-HR
CORR. BSFC - = .430 LBS/BHP-HR

TABLE H-2. SUPPLEMENTARY ENGINE DATA OBTAINED OVER 13-MODE TESTING ON (EM-600-F) DISTILLATE

Test Mode No.	Fuel		Inlet Air			Exhaust		Oil	
	Temp.[a] °F	Press.[b] psi	Temp. °F	Restrict. in. H_2O	Boost psi	Temp. °F	B.P. in. H_2O	Temp. °F	Press. psi
1	94	32.5	78	1.1	0	319	0	212	22
2	94	52.0	77	5.2	0.5	328	0.2	198	48
3	93	51.0	76	5.7	1.4	480	0.25	198	48
4	93	49.5	75	6.7	3.6	677	0.30	203	47
5	93	48.5	76	8.5	6.8	857	0.50	207	46
6	94	46.0	76	9.6	10.2	1002	0.70	212	43
7	95	32.5	79	1.1	0	310	0	204	20
8	92	59.0	75	24.9	16.6	997	2.0	210	47
9	95	59.5	77	18.1	11.5	862	1.5	226	46
10	97	61.0	77	13.8	7.0	739	0.90	224	47
11	97	63.0	77	10.8	3.7	589	0.65	220	48
12	97	64.5	76	9.0	1.6	435	0.45	215	49
13	96	32.0	78	1.1	0	275	0	202	21

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[a] Measured at fuel inlet to pump

[b] Measured after secondary filter

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                        TABLE H-3. ENGINE EMISSION RESULTS
                                   C-TRANS.                              PROJECT NO. 03-7774-002

ENGINE  NO.                               TEST NO.3      RUN1
ENGINE  MODEL     0 IHC DT466B            DATE  7/24/84
ENGINE  7.6 L(466. CID) L-6               TIME                                 DIESEL   EM-600-F
CVS NO.  11                               DYNO NO.  1                          BAG CART NO.  1

BAROMETER 742.70 MM HG(29.24 IN HG)       RELATIVE HUMIDITY ,  ENGINE-61. PCT ,  CVS-64. PCT
DRY BULB TEMP. 22.8 DEG C(73.0 DEG F)     ABSOLUTE HUMIDITY 10.9 GM/KG( 76.5 GRAINS/LB)      NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                   1                   2                   3                   4
  DESCRIPTION                                NYNF                LANF                 LAF                NYNF
  TIME SECONDS                              296.0               300.0               305.0               298.0
  TOT. BLOWER RATE SCMM (SCFM)        83.36 ( 2943.4)     83.33 ( 2942.5)     83.35 ( 2943.1)     83.35 ( 2943.0)
  TOT. 20X20 RATE SCMM (SCFM)          9.77 (344.9)        9.77 (344.9)        9.77 (344.9)        9.77 (344.9)
  TOT. 90MM RATE SCMM (SCFM)            .03 (  .90)         .03 (  .90)         .03 (  .90)         .03 (  .90)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)     .05 ( 1.65)         .05 ( 1.65)         .05 ( 1.65)         .05 ( 1.65)
  TOTAL FLOW STD. CU. METRES(SCF)     459.8 (  16235.)    465.9 (16450.)      473.7 (16727.)      462.8 (16343.)

  HC   SAMPLE METER/RANGE/PPM          55.9/21/  28.       43.3/21/  22.       45.7/21/  23.       34.8/21/  17.
  HC   BCKGRD METER/RANGE/PPM          17.0/ 1/   9.       17.8/ 1/   9.       17.7/ 1/   9.       17.5/ 1/   9.
  CO   SAMPLE METER/RANGE/PPM          37.8/13/  35.       24.9/13/  23.       19.4/13/  18.       14.0/13/  13.
  CO   BCKGRD METER/RANGE/PPM           1.0/13/   1.        1.4/13/   1.        1.5/13/   1.        1.5/13/   1.
  CO2  SAMPLE METER/RANGE/PCT          82.1/13/  .17       59.4/12/  .24       65.5/11/  .55       73.8/13/  .15
  CO2  BCKGRD METER/RANGE/PCT          22.2/13/  .04       12.4/12/  .04        7.2/11/  .04       22.5/13/  .04
  NOX  SAMPLE METER/RANGE/PPM          61.5/ 1/  18.       86.4/ 1/  26.       71.5/ 2/  72.       60.7/ 1/  18.
  NOX  BCKGRD METER/RANGE/PPM            .7/ 1/   0.        1.5/ 1/   0.         .6/ 2/   1.        1.8/ 1/   1.

  DILUTION FACTOR                          75.15               55.14               24.16               86.60
  HC   CONCENTRATION PPM                   20.                 13.                 14.                  9.
  CO   CONCENTRATION PPM                   33.                 21.                 16.                 11.
  CO2  CONCENTRATION PCT                    .13                 .20                 .51                 .11
  NOX  CONCENTRATION PPM                   18.1                25.3                70.9                17.5

  HC   MASS GRAMS                           5.19                3.47                3.92                2.34
  CO   MASS GRAMS                          17.86               11.38                8.73                5.97
  CO2  MASS GRAMS                        1108.4              1682.6              4431.9               937.9
  NOX  MASS GRAMS                          15.91               22.51               64.25               15.51
  FUEL KG (LB)                        .369 (      .81)   .548 (     1.21)   1.428 (     3.15)   .306 (      .67)
  KW HR (HP HR)                       1.08 (     1.45)   1.88 (     2.52)    5.61 (     7.52)   1.10 (     1.47)

  BSHC G/KW HR (G/HP HR)              4.80 (     3.58)   1.85 (     1.38)     .70 (      .52)   2.14 (     1.59)
  BSCO G/KW HR (G/HP HR)             16.51 (    12.31)   6.05 (     4.52)    1.56 (     1.16)   5.44 (     4.06)
  BSCO2 G/KW HR (G/HP HR)          1025.08 (  764.40)  895.40 (  667.70)  790.32 (  589.35)  855.57 (  638.00)
  BSNOX G/KW HR (G/HP HR)            14.71 (    10.97)  11.98 (     8.93)   11.46 (     8.54)  14.15 (    10.55)
  BSFC KG/KW HR (LB/HP HR)            .342 (     .562)   .292 (     .480)    .255 (     .419)   .279 (     .459)

TOTAL TEST RESULTS 4 BAGS                            PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)           9.66 ( 12.96)        90MM PARTICULATE RATES    GRAMS/TEST               11.25
  BSHC   G/KW HR (G/HP HR)      1.54 (  1.15)                                  G/KWHR(G/HPHR)        1.16  (  .87)
  BSCO   G/KW HR (G/HP HR)      4.55 (  3.39)                                  G/KG FUEL (G/LB FUEL) 4.24  ( 1.92)
  BSCO2  G/KW HR (G/HP HR)      844. (  630.)                                  FILTER EFF.              91.8
  BSNOX  G/KW HR (G/HP HR)     12.23 (  9.12)
  BSFC   KG/KW HR (LB/HP HR)    .274 (  .451)
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                                   TABLE  H-3. ENGINE EMISSION RESULTS  (Cont'd)
                                                   H-TRANS.                                   PROJECT NO. 03-7774-002

ENGINE  NO.                                   TEST NO.3       RUN1
ENGINE  MODEL     0 IHC DT466B                DATE  7/24/84
ENGINE  7.6 L(466. CID) L-6                   TIME                                DIESEL    EM-600-F
CVS NO.  11                                   DYNO NO.  1                         BAG CART NO.  1

BAROMETER 742.70 MM HG(29.24 IN HG)           RELATIVE HUMIDITY ,  ENGINE-56. PCT ,  CVS-57. PCT
DRY BULB TEMP. 21.7 DEG C(71.0 DEG F)         ABSOLUTE HUMIDITY  9.4 GM/KG( 65.5 GRAINS/LB)       NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                        1                   2                   3                   4
  DESCRIPTION                                     NYNF                LANF                 LAF                NYNF
  TIME SECONDS                                    296.0               300.0               305.0               298.0
  TOT. BLOWER RATE SCMM (SCFM)              83.35 ( 2943.1)     83.33 ( 2942.5)     83.37 ( 2943.8)     83.36 ( 2943.3)
  TOT. 20X20 RATE SCMM (SCFM)                9.80 (346.0)        9.80 (346.0)        9.80 (346.0)        9.80 (346.0)
  TOT. 90MM RATE SCMM (SCFM)                  .03 (   .91)        .03 (   .91)        .03 (   .91)        .03 (   .91)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)           .05 ( 1.61)         .05 ( 1.61)         .05 ( 1.61)         .05 ( 1.61)
  TOTAL FLOW STD. CU. METRES(SCF)           459.9 (  16238.)    466.0 (16455.)      474.0 (16736.)      463.0 (16349.)

  HC   SAMPLE METER/RANGE/PPM               33.0/21/  16.       36.0/21/  18.       41.9/21/  21.       33.9/21/  17.
  HC   BCKGRD METER/RANGE/PPM               15.0/ 1/   8.       14.6/ 1/   7.       14.5/ 1/   7.       16.0/ 1/   8.
  CO   SAMPLE METER/RANGE/PPM               18.1/13/  16.       18.1/13/  16.       17.2/13/  16.       13.9/13/  13.
  CO   BCKGRD METER/RANGE/PPM                1.0/13/   1.        1.0/13/   1.        1.5/13/   1.        1.5/13/   1.
  CO2 SAMPLE METER/RANGE/PCT                73.5/13/  .15       57.8/12/  .23       64.1/11/  .53       72.2/13/  .15
  CO2 BCKGRD METER/RANGE/PCT                21.9/13/  .04       11.8/12/  .04        7.0/11/  .04       21.9/13/  .04
  NOX SAMPLE METER/RANGE/PPM                60.3/ 1/  18.       87.9/ 1/  26.       70.6/ 2/  71.       59.0/ 1/  18.
  NOX BCKGRD METER/RANGE/PPM                 1.7/ 1/   0.        1.9/ 1/   1.         .5/ 2/   1.        1.9/ 1/   1.

  DILUTION FACTOR                                86.84               57.17               24.91               88.79
  HC   CONCENTRATION PPM                          9.                 11.                 14.                  9.
  CO   CONCENTRATION PPM                         15.                 15.                 14.                 11.
  CO2 CONCENTRATION PCT                          .11                 .19                 .50                 .11
  NOX CONCENTRATION PPM                         17.4                25.6                70.1                17.0

  HC   MASS GRAMS                                2.41                2.90                3.82                2.41
  CO   MASS GRAMS                                8.15                8.25                7.67                5.94
  CO2 MASS GRAMS                                935.8              1635.4              4301.8               916.2
  NOX MASS GRAMS                                15.34               22.81               63.56               15.05
  FUEL KG (LB)                              .306 (    .68)      .531 (   1.17)     1.386 (   3.06)      .299 (    .66)
  KW HR (HP HR)                             1.10 (   1.48)      1.89 (   2.53)      5.60 (   7.51)      1.08 (   1.45)

  BSHC G/KW HR (G/HP HR)                    2.18 (   1.63)      1.54 (   1.15)       .68 (    .51)      2.23 (   1.66)
  BSCO G/KW HR (G/HP HR)                    7.38 (   5.51)      4.37 (   3.26)      1.37 (   1.02)      5.49 (   4.09)
  BSCO2 G/KW HR (G/HP HR)                 847.92 ( 632.30)    866.85 ( 646.41)    768.15 ( 572.81)    847.33 ( 631.85)
  BSNOX G/KW HR (G/HP HR)                  13.90 (  10.36)     12.09 (   9.02)     11.35 (   8.46)     13.92 (  10.38)
  BSFC KG/KW HR (LB/HP HR)                  .278 (   .456)      .281 (   .463)      .248 (   .407)      .276 (   .455)

TOTAL TEST RESULTS 4 BAGS                                 PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)           9.67 ( 12.97)             90MM PARTICULATE RATES    GRAMS/TEST                     8.80
  BSHC   G/KW HR (G/HP HR)      1.19 (   .89)                                       G/KWHR(G/HPHR)            .91  (  .68)
  BSCO   G/KW HR (G/HP HR)      3.10 (  2.31)                                       G/KG FUEL (G/LB FUEL)    3.49  ( 1.58)
  BSCO2  G/KW HR (G/HP HR)      805. (  601.)                                       FILTER EFF.                    91.7
  BSNOX  G/KW HR (G/HP HR)     12.07 (  9.00)
  BSFC   KG/KW HR (LB/HP HR)    .261 (  .429)
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                              TABLE H-4.  ENGINE EMISSION RESULTS
                                             C-TRANS.                                    PROJECT NO. 03-7774-002

ENGINE  NO.                                      TEST NO.3      RUN2
ENGINE  MODEL    0 IHC DT466B                    DATE  7/24/84
ENGINE  7.6 L(466. CID) L-6                      TIME                          DIESEL   EM-600-F
CVS NO.  11                                      DYNO NO.  1                   BAG CART NO.  1

BAROMETER 744.47 MM HG(29.31 IN HG)              RELATIVE HUMIDITY , ENGINE-65. PCT ,  CVS-64. PCT
DRY BULB TEMP. 22.2 DEG C(72.0 DEG F)            ABSOLUTE HUMIDITY 11.1 GM/KG( 77.9 GRAINS/LB)      NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                        1                  2                  3                  4
  DESCRIPTION                                      NYNF               LANF               LAF                NYNF
  TIME SECONDS                                    296.0              300.0              305.0              298.0
  TOT. BLOWER RATE SCMM (SCFM)               83.73 ( 2956.4)    83.71 ( 2955.8)    83.72 ( 2956.1)    83.56 ( 2950.6)
  TOT. 20X20 RATE SCMM (SCFM)                 9.83 (347.2)       9.83 (347.2)       9.83 (347.2)       9.83 (347.2)
  TOT. 90MM RATE SCMM (SCFM)                   .03 (  .91)        .03 (  .91)        .03 (  .91)        .03 (  .91)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)            .05 ( 1.64)        .05 ( 1.64)        .05 ( 1.64)        .05 ( 1.64)
  TOTAL FLOW STD. CU. METRES(SCF)            461.9 (  16310.)   468.1 (16528.)     475.9 (16805.)     464.2 (16392.)

  HC  SAMPLE METER/RANGE/PPM                 54.5/21/  27.      40.7/21/  20.      42.4/21/  21.      37.0/21/  18.
  HC  BCKGRD METER/RANGE/PPM                 17.7/ 1/   9.      18.2/ 1/   9.      18.2/ 1/   9.      19.4/ 1/  10.
  CO  SAMPLE METER/RANGE/PPM                 35.9/13/  33.      23.7/13/  22.      17.5/13/  16.      13.6/13/  12.
  CO  BCKGRD METER/RANGE/PPM                  1.3/13/   1.       1.4/13/   1.       1.3/13/   1.       1.7/13/   2.
  CO2 SAMPLE METER/RANGE/PCT                 79.4/13/  .17      58.5/12/  .23      63.1/11/  .52      72.6/13/  .15
  CO2 BCKGRD METER/RANGE/PCT                 21.6/13/  .04      12.0/12/  .04       7.0/11/  .04      21.8/13/  .04
  NOX SAMPLE METER/RANGE/PPM                 59.6/ 1/  18.      85.0/ 1/  25.      68.5/ 2/  69.      58.9/ 1/  18.
  NOX BCKGRD METER/RANGE/PPM                   .7/ 1/   0.       1.1/ 1/   0.        .4/ 2/   0.       1.1/ 1/   0.

  DILUTION FACTOR                                 78.24              56.19              25.45              88.17
  HC  CONCENTRATION PPM                           19.                11.                12.                 9.
  CO  CONCENTRATION PPM                           31.                20.                14.                11.
  CO2 CONCENTRATION PCT                           .13                .19                .48                .11
  NOX CONCENTRATION PPM                           17.5               25.0               68.1               17.2

  HC  MASS GRAMS                                  4.94               3.07               3.41               2.38
  CO  MASS GRAMS                                 16.83              10.84               7.93               5.70
  CO2 MASS GRAMS                                1065.9             1665.4             4218.7              928.2
  NOX MASS GRAMS                                 15.48              22.35              61.99              15.27
  FUEL KG (LB)                               .355 (     .78)   .542 (    1.20)   1.359 (    3.00)   .303 (     .67)
  KW HR (HP HR)                              1.09 (    1.46)   1.89 (    2.54)   5.62 (    7.54)   1.11 (    1.49)

  BSHC G/KW HR (G/HP HR)                     4.53 (    3.38)   1.62 (    1.21)    .61 (     .45)   2.14 (    1.60)
  BSCO G/KW HR (G/HP HR)                    15.46 (   11.53)   5.72 (    4.27)   1.41 (    1.05)   5.13 (    3.82)
  BSCO2 G/KW HR (G/HP HR)                  979.08 (  730.10) 879.28 (  655.68) 750.31 (  559.51) 835.43 (  622.98)
  BSNOX G/KW HR (G/HP HR)                   14.22 (   10.60)  11.80 (    8.80)  11.03 (    8.22)  13.74 (   10.25)
  BSFC KG/KW HR (LB/HP HR)                   .326 (    .536)   .286 (    .471)   .242 (    .397)   .272 (    .448)

TOTAL TEST RESULTS 4 BAGS                              PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)            9.72 ( 13.03)         90MM PARTICULATE RATES     GRAMS/TEST                12.84
  BSHC  G/KW HR (G/HP HR)        1.42 (  1.06)                                    G/KWHR(G/HPHR)        1.32  (  .99)
  BSCO  G/KW HR (G/HP HR)        4.25 (  3.17)                                    G/KG FUEL (G/LB FUEL) 5.02  ( 2.28)
  BSCO2 G/KW HR (G/HP HR)        811. (  605.)                                    FILTER EFF.               93.2
  BSNOX G/KW HR (G/HP HR)       11.85 (  8.83)
  BSFC  KG/KW HR (LB/HP HR)      .263 (  .433)
```

```
                        TABLE H-4. ENGINE EMISSION RESULTS (Cont'd)
                                    H-TRANS.                                    PROJECT NO. 03-7774-002

ENGINE  NO.                                    TEST NO.3      RUN2
ENGINE  MODEL     0 IHC DT466B                 DATE  7/25/84
ENGINE  7.6 L(466. CID) L-6                    TIME                            DIESEL   EM-600-F
CVS NO.  11                                    DYNO NO.  1                     BAG CART NO.  1

BAROMETER 744.22 MM HG(29.30 IN HG)            RELATIVE HUMIDITY ,  ENGINE-62. PCT ,  CVS-62. PCT
DRY BULB TEMP. 23.9 DEG C(75.0 DEG F)          ABSOLUTE HUMIDITY 11.9 GM/KG( 83.0 GRAINS/LB)     NOX HUMIDITY C.F. 1.0000

BAG RESULTS
  BAG NUMBER                                   1                2                3                4
  DESCRIPTION                                NYNF             LANF              LAF             NYNF
  TIME SECONDS                              296.0            300.0            305.0            298.0
  TOT. BLOWER RATE SCMM (SCFM)        83.66 ( 2953.9)  83.64 ( 2953.3)  83.67 ( 2954.3)  83.65 ( 2953.8)
  TOT. 20X20 RATE SCMM (SCFM)          9.79 (345.5)     9.79 (345.5)     9.79 (345.5)     9.79 (345.5)
  TOT. 90MM RATE SCMM (SCFM)            .03 (  .90)      .03 (  .90)      .03 (  .90)      .03 (  .90)
  TOT. AUX. SAMPLE RATE SCMM (SCFM)     .05 ( 1.69)      .05 ( 1.69)      .05 ( 1.69)      .05 ( 1.69)
  TOTAL FLOW STD. CU. METRES(SCF)     461.3 (  16290.) 467.5 (16507.)   475.4 (16787.)   464.4 (16399.)

  HC  SAMPLE METER/RANGE/PPM          39.4/21/  20.    42.0/21/  21.    45.5/21/  23.    38.9/21/  19.
  HC  BCKGRD METER/RANGE/PPM          13.8/ 1/   7.    14.8/ 1/   7.    15.0/ 1/   8.    15.5/ 1/   8.
  CO  SAMPLE METER/RANGE/PPM          19.6/13/  18.    17.5/13/  16.    16.3/13/  15.    13.1/13/  12.
  CO  BCKGRD METER/RANGE/PPM           1.2/13/   1.     1.6/13/   1.     1.8/13/   2.     1.5/13/   1.
  CO2 SAMPLE METER/RANGE/PCT          71.2/13/  .15    57.3/12/  .23    61.7/11/  .51    71.4/13/  .15
  CO2 BCKGRD METER/RANGE/PCT          21.6/13/  .04    12.1/12/  .04     7.1/11/  .04    21.7/13/  .04
  NOX SAMPLE METER/RANGE/PPM          55.8/ 1/  17.    85.9/ 1/  26.    66.3/ 2/  66.    57.3/ 1/  17.
  NOX BCKGRD METER/RANGE/PPM            .8/ 1/   0.     1.3/ 1/   0.      .4/ 2/   0.     1.2/ 1/   0.

  DILUTION FACTOR                          89.72            57.70            26.24            89.80
  HC  CONCENTRATION PPM                    13.              14.              16.              12.
  CO  CONCENTRATION PPM                    16.              14.              13.              10.
  CO2 CONCENTRATION PCT                    .11              .19              .47              .11
  NOX CONCENTRATION PPM                   16.4             25.2             65.9             16.7

  HC  MASS GRAMS                           3.42             3.69             4.25             3.16
  CO  MASS GRAMS                           8.80             7.68             7.10             5.56
  CO2 MASS GRAMS                          898.1           1611.2           4070.1            906.4
  NOX MASS GRAMS                          14.44            22.51            59.93            14.83
  FUEL KG (LB)                        .296 (    .65)  .524 (   1.15)  1.312 (   2.89)  .296 (    .65)
  KW HR (HP HR)                       1.11 (   1.49)  1.91 (   2.56)   5.62 (   7.54)  1.11 (   1.49)

  BSHC G/KW HR (G/HP HR)              3.08 (   2.30)  1.94 (   1.44)    .76 (    .56)  2.85 (   2.12)
  BSCO G/KW HR (G/HP HR)              7.92 (   5.90)  4.03 (   3.00)   1.26 (    .94)  5.00 (   3.73)
  BSCO2 G/KW HR (G/HP HR)           808.26 ( 602.72) 844.02 ( 629.38) 723.89 ( 539.80) 815.76 ( 608.31)
  BSNOX G/KW HR (G/HP HR)            12.99 (   9.69) 11.79 (   8.79)  10.66 (   7.95)  13.34 (   9.95)
  BSFC KG/KW HR (LB/HP HR)            .266 (   .437)  .274 (   .451)   .233 (   .384)  .267 (   .439)

 TOTAL TEST RESULTS 4 BAGS                     PARTICULATE RESULTS, TOTAL FOR 4 BAGS

  TOTAL KW HR (HP HR)          9.75 ( 13.08)   90MM PARTICULATE RATES    GRAMS/TEST                 8.28
  BSHC  G/KW HR (G/HP HR)      1.49 (  1.11)                             G/KWHR(G/HPHR)           .85  (  .63)
  BSCO  G/KW HR (G/HP HR)      2.99 (  2.23)                             G/KG FUEL (G/LB FUEL)   3.41  ( 1.55)
  BSCO2 G/KW HR (G/HP HR)      767. (  572.)                             FILTER EFF.                91.9
  BSNOX G/KW HR (G/HP HR)     11.45 (  8.54)
  BSFC  KG/KW HR (LB/HP HR)    .249 (  .409)
```

TABLE H-5. INDIVIDUAL HYDROCARBONS FROM COLD START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-600-F) DISTILLATE

Individual HC from Test 7, Run 1, 7/24/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	160	17	60
Ethylene	1000	100	380
Ethane	0	0	0
Acetylene	74	7.7	28
Propane	0	0	0
Propylene	400	41	150
Benzene	120	12	45
Toluene	0	0	0

Individual HC from Test 7, Run 2, 7/25/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	220	23	86
Ethylene	730	75	290
Ethane	0	0	0
Acetylene	37	3.8	14
Propane	0	0	0
Propylene	350	36	140
Benzene	0	0	0
Toluene	0	0	0

Average HC from Test 7, Runs 1 and 2

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	190	20	73
Ethylene	870	88	340
Ethane	0	0	0
Acetylene	56	5.8	21
Propane	0	0	0
Propylene	380	39	150
Benzene	60	6.0	23
Toluene	0	0	0

TABLE H-6. INDIVIDUAL HYDROCARBONS FROM HOT START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-600-F) DISTILLATE

Individual HC from Test 7, Run 1, 7/24/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	0	0	0
Ethylene	680	70	270
Ethane	0	0	0
Acetylene	43	4.4	17
Propane	0	0	0
Propylene	220	23	87
Benzene	0	0	0
Toluene	0	0	0

Individual HC from Test 7, Run 2, 7/25/84

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	99	10	41
Ethylene	1000	100	410
Ethane	0	0	0
Acetylene	79	8.1	33
Propane	0	0	0
Propylene	320	33	130
Benzene	77	7.9	32
Toluene	0	0	0

Average HC from Test 7, Runs 1 and 2

Hydrocarbon	mg/test	mg/kW-hr	mg/kg fuel
Methane	50	5.0	21
Ethylene	840	85	340
Ethane	0	0	0
Acetylene	61	6.3	25
Propane	0	0	0
Propylene	270	28	110
Benzene	39	4.0	16
Toluene	0	0	0

TABLE H-7. ALDEHYDES FROM COLD START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-600-F) DISTILLATE

Aldehydes from Test 7, Run 1, 7/24/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1259	130	475
Acetaldehyde	401	41.5	151
Acrolein	0	0	0
Acetone	307	31.8	116
Propionaldehyde	0	0	0
Crotonaldehyde	100	10.4	37.7
Isobutyraldehyde & Methylethylketone	198	20.5	74.7
Benzaldehyde	75.9	7.86	28.6
Hexanaldehyde	55.1	5.70	20.8

Aldehydes from Test 7, Run 2, 7/25/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1014	104	396
Acetaldehyde	250	25.7	97.7
Acrolein	126	13.0	49.2
Acetone	316	32.5	123
Propionaldehyde	0	0	0
Crotonaldehyde	44.7	4.60	17.5
Isobutyraldehyde & Methylethylketone	152	15.6	59.4
Benzaldehyde	48.3	4.97	18.9
Hexanaldehyde	100	10.3	39.1

Average Aldehydes from Test 7, Runs 1 and 2

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	1137	117	436
Acetaldehyde	326	33.6	124
Acrolein	63	6.50	24.6
Acetone	312	32.2	120
Propionaldehyde	0	0	0
Crotonaldehyde	72.4	7.50	27.6
Isobutyraldehyde & Methylethylketone	175	18.1	67.1
Benzaldehyde	62.1	6.42	23.8
Hexanaldehyde	77.6	8.00	30.0

TABLE H-8. ALDEHYDES FROM HOT START TRANSIENT OPERATION OF THE IH DT-466B ON (EM-600-F) DISTILLATE

Aldehydes from Test 7, Run 1, 7/24/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	955	98.8	379
Acetaldehyde	276	28.5	110
Acrolein	235	24.3	93.3
Acetone	307	31.7	122
Propionaldehyde	0	0	0
Crotonaldehyde	103	10.7	40.9
Isobutyraldehyde & Methylethylketone	198	20.5	78.6
Benzaldehyde	76	7.86	30.2
Hexanaldehyde	55	5.69	21.8

Aldehydes from Test 7, Run 2, 7/25/84

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	570	58.5	235
Acetaldehyde	240	24.6	98.8
Acrolein	13.2	1.35	5.43
Acetone	141	14.5	58.0
Propionaldehyde	244	25.0	100
Crotonaldehyde	46.7	4.79	19
Isobutyraldehyde & Methylethylketone	0	0	0
Benzaldehyde	0	0	0
Hexanaldehyde	0	0	0

Average Aldehydes from Test 7, Runs 1 and 2

Aldehyde	mg/test	mg/kW-hr	mg/kg fuel
Formaldehyde	763	78.7	307
Acetaldehyde	258	26.6	104
Acrolein	124	12.8	98.7
Acetone	224	23.1	90.0
Propionaldehyde	122	12.5	50.0
Crotonaldehyde	74.9	7.75	30.0
Isobutyraldehyde & Methylethylketone	99.0	10.3	39.3
Benzaldehyde	38.0	3.93	15.1
Hexanaldehyde	27.5	2.85	10.9

TABLE H-9. **FEDERAL SMOKE TEST TRACE EVALUATION**

Engine Model: IH DT-466 B Test No. 3 Date: 7/23/84
Engine S/N: Fuel: EM-600-F Run No. 1 Eval. By: K. Jack

Accelerations Observed Power: 205. hp Barometer: 29.19

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	9.2	1	7.0	1	7.5
2	8.3	2	8.2	2	14.0
3	8.7	3	5.9	3	10.5
4	14.0	4	10.0	4	12.7
5	20.0	5	16.0	5	17.0
6	10.2	6	20.3	6	18.0
7	6.7	7	9.5	7	11.0
8	5.8	8	7.4	8	10.0
9	12.5	9	7.0	9	7.8
10	12.4	10	13.3	10	13.0
11	6.0	11	14.0	11	13.3
12	5.3	12	8.0	12	9.0
13	5.0	13	5.6	13	6.2
14	4.7	14	4.8	14	6.5
15	4.8	15	5.3	15	6.7
Total Smoke %	133.6		142.3		163.2

Factor (a) = $\frac{439.1}{45}$ = 9.8 %

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	4.2	1	3.0	1	5.0
2	3.8	2	3.7	2	4.7
3	4.9	3	2.8	3	5.7
4	5.5	4	3.0	4	5.0
5	4.8	5	3.5	5	5.4
Total Smoke %	23.2		16.0		25.8

Factor (b) = $\frac{65.0}{15}$ = 4.3 %

Peak

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	20.0	1	20.3	1	18.0
2	14.0	2	16.0	2	17.0
3	12.5	3	14.0	3	14.0
Total Smoke %	46.5		50.3		49.0

Factor (c) = $\frac{145.8}{9}$ = 16.2 %

APPENDIX I

RESULTS FROM BORESCOPE INSPECTION AFTER OPERATION ON MINIMALLY-PROCESSED SHALE OILS

TABLE I-1

Borescope Inspection Report No. 8

Date: 7/18/84 Engine Hours: 26ⓐ Fuel Code: EM-597-F

Engine Manufacturer/Designation IH / DT-466B Serial No. —

Cylinder Liner No.

1. Clear, T; Clear, AT
2. Clear, T; Clear, AT
3. Clear, T; Clear, AT
4. Clear, T; Clear, AT
5. Clear, T; 2% BP, AT
6. Clear, T; 1% BP, AT

Notes: [a] Engine was rebuilt with new pistons, rings, liners, rod end bearings, valve job. Required breakin + 20 hr of maximum power operation on DF-2 prior to emissions testing. Six hours for emissions testwork.

Terms:

"Streaking," faint lines (appearing like pencil lines) along the stroke of the cylinder wall

"BP," Bore Polish, a smoothing of the liner with the cross-hatch still visible

"S," Scuffing, roughning of liner with no cross-hatch visible.

"T," Thrust, right side of liner on a right rotation engine

"AT," Anti-Thrust, left side of liner on a right rotation engine

TABLE I-2

Borescope Inspection Report No. 9

Date: 7/20/84 Engine Hours: 31[a] Fuel Code: EM-599-F

Engine Manufacturer/Designation IH / DT-466-B Serial No. ——

Cylinder Liner No.

1. Clear, T; 10% BP, AT
2. Clear, T; Clear, AT
3. Clear, T; Clear, AT
4. Clear, T; Clear, AT
5. 4% BP, T; 5% BP, AT
6. Clear T; 1% BP, AT

Notes: [a] Approx. 5 hrs on EM-599-F

Gray colored spots on piston crowns, piston appear to have a reddish tint

Terms:

"Streaking," faint lines (appearing like pencil lines) along the stroke of the cylinder wall

"BP," Bore Polish, a smoothing of the liner with the cross-hatch still visible

"S," Scuffing, roughning of liner with no cross-hatch visible.

"T," Thrust, right side of liner on a right rotation engine

"AT," Anti-Thrust, left side of liner on a right rotation engine

TABLE I-3

Borescope Inspection Report No. 10

Date: 7/25/84 Engine Hours: 37[a] Fuel Code: EM-600-F

Engine Manufacturer/Designation IH / DT-466B Serial No. —

Cylinder Liner No.

1. Clear, T; 10% BP, AT
2. Clear, T; Clear, AT
3. Clear, T; Clear, AT
4. Clear, T; Clear, AT
5. 4% BP, T; 5% BP, AT
6. 1% BP, T; 2% BP, AT

Notes: [a] Approx. 6 hrs on EM-600-F

Pistons have a gray tint - no carbon build-up, good fire pattern

Terms:

"Streaking," faint lines (appearing like pencil lines) along the stroke of the cylinder wall

"BP," Bore Polish, a smoothing of the liner with the cross-hatch still visible

"S," Scuffing, roughning of liner with no cross-hatch visible.

"T," Thrust, right side of liner on a right rotation engine

"AT," Anti-Thrust, left side of liner on a right rotation engine

APPENDIX J

RESULTS FROM BIOASSAY OF SOF FROM OPERATION ON DF-2 AND CRUDE AND MINIMALLY-PROCESSED SHALE OILS

Southwest Foundation
for Biomedical Research

West Loop 410 at Military Drive
P.O. Box 28147
San Antonio, Texas 78284
(512) 674-1410

November 9, 1984

Analysis of Seven Diesel Extracts for Mutagenic Activity

Arnaldo J Noyola
Arnaldo J. Noyola, M.A.
Senior Research Associate

Milton V. Marshall
Milton V. Marshall, Ph.D.
Associate Scientist

Introduction

Seven samples were received for analysis of mutagenic activity in *S. typhimurium* tester strains TA97, TA98, TA100, TA102, and TA98NR. A description of the samples is given below:

Sample Identification	Weight (mg)	Date Received
366 EM-528-F	506.9	April 30, 1984
367 EM-584-F	569.9	April 30, 1984
368 EM-586-F	497.5	April 30, 1984
369 EM-585-F	514.2	April 30, 1984
568 EM-597-F (DF-2)	251.1	August 29, 1984
626 EM-599-F	254.7	August 29, 1984
580 EM-600-F	266.7	August 29, 1984

These samples were analyzed for mutagenic activity in five tester strains at levels of 20, 60, 100, 200, 400, 600, and 1000 µg in the presence and absence of an Aroclor-induced rat liver homogenate (S9), batch RLA005. Replicate analyses were performed on each sample.

Results

Difficulties were encountered when tester strain TA97 was first employed. (See note from Bruce Ames in Appendix.) Therefore, TA97a was substituted for TA97 for analyzing the mutagenic activity of the samples. A comparison of the positive and negative controls for TA97 and TA97A are given below:

	His$^+$ Revertants/Plate		
Treatment	TA97	TA97A (initial)	TA97A (repeat)
Medium	184	93	131
DMSO	165	92	126
S9 (RLA005 @ 50 l)	232	167	178
1-Nitropyrene (1 g)	239	438	485
ICR-191 (1 g)	1959	2091	2104
2-Aminofluorene + S9 (10 g)	359	380	390

A slightly better response to the diagnostic mutagens was obtained with tester strain TA97A, compared to TA97. The data obtained for the mutagenic response of sample number 366 in both TA97 and TA97A is given in Figure 1. The dose-response curve was better for this sample in TA97A than in TA97. The slopes of the linear portion of the dose-response curves, obtained from regression analysis, were 1.200 revertants/μg in TA97, 1.263 revertants/μg in TA97A (initial) and 0.971 revertants/μg in TA97A (repeat) for samples treated in the absence of S9. In the presence of S9, 0.625 revertants/μg were obtained in TA97, 0.349 revertants/μg in TA97A (initial), and 0.483 revertants/μg in TA97A (repeat).

The positive and negative controls for all seven samples are given in Table 1. Table 2 shows the cumulative means and standard deviations obtained with the different tester strains. Although TA102 did not always fall within the recommended spontaneous reversion frequency of 300 ± 60, the mutagenic response to cumene hydroperoxide was less variable. TA102 was routinely grown up on master plates as recommended by Ames (Appendix), whereas the other strains were grown from frozen stocks.

A comparison of the mutagenic activity of the seven samples is given in Table 3. The lowest mutagenic response was obtained in tester strain TA98NR, a nitroreductase-deficient strain derived from TA98. This strain is insensitive to the mutagenic activity of 1-nitropyrene, which has been reported to account for most of the mutagenic activity associated with diesel exhaust extract. The raw data and plots of the dose-response curves are shown in Figures 2-22.

Conclusion

Mutagenic activity was observed in the presence and absence of S9 for all samples tested. Additional comments submitted December 24, 1985 are given on the following page.

MEMORANDUM

To: Terry Ullman
From : Milton Marshall M Marshall
Subject: Report on 7 diesel extracts obtained from shale oils
Date : December 24, 1984

I would like to expand the Conclusion section of my report of November 9, 1984 to include the following information:

Since no good dose-response relationships were obtained with tester strain TA102, this strain is omitted from the discussion. Ames recommends that the revertants per plate should be taken from the linear portion of the dose-response curve. In calculating the revertants/ug extract, the linear portion of the dose-response curve was analyzed by linear regression. If a curvilinear response was observed (as we usually found with TA102), three data points were used for slope determination. In all instances, a minimum of three data points were analyzed per condition in each tester strain. When the average mutagenic activity (his+ revertants/ug extract) of the 7 samples was ranked in tester strains TA97a, TA98, TA98NR, and TA100, a good correlation was obtained with levels of 1-nitropyrene (1NP) expressed in ug/g SOF for these samples. The greatest mutagenic response was obtained with sample #568 in TA97a in the absence of S9. (TA97a has now replaced TA97, see Appendix. For purposes of this discussion, the mutagenic response should be similar in these two isogenic strains.) Compounds that are active in TA97 include benzo(a)pyrene (BaP), which is more active as a frameshift mutagen in TA97 than in TA98 in the presence of S9. (BaP also induces base pair substitution mutations which are detected in TA100.) Nitro-PAHs also are detected in TA97 as well as in TA98.

TA98NR is insensitive to the mutagenic effects of 1NP, but not to dinitropyrenes, in the absence of S9. The lack of an increase in the ratio of revertants/ug extract in TA98 compared to TA98NR indicates that the mutagenic activity observed in TA98 may not be accounted for by the presence of 1NP which is most active in TA98. This observation, coupled with the mutagenic activity observed in TA100, indicates that the major mutagenic species in these diesel extracts is probably not 1NP. However, other nitro-PAHs cannot be excluded since their responses in TA98NR are unknown, and the relative amounts of 1NP are probably indicative of total nitro-PAHs present in the extracts. Also, nitro-PAHs are detoxified rather than activated by mixed function oxidase enzymes present in the S9.

In summary, I feel that the majority of the mutagenic activity observed in these extracts is not due to 1NP, but to other constituents of the diesel exhaust extracts. Some of these components may be acting synergistically, or the activity may be due to the presence of other compounds, possibly nitro-PAHs other than 1NP.

Table 1. Positive and Negative Controls

Controls		TA97A	TA98	TA100	TA102	TA98NR
INITIAL #366	Medium	93	16	100	239	15
	DMSO	92	14	94	232	14
	S9 (RLA005)	167	23	100	396	19
	1-NP[b] (1 μg)	438	561	131	283	45
	ICR-191 (1 μg)	2091				
	2-NF (5 μg)		464			
	NaN_3 (1 μg)			339		
	Cum. HPx[d] (50 μg)				1356	
	2,4,7-TNF[e] (0.25 μg)					966
	2-AF + S9 (10 μg)	380	737	397	513	760
REPEAT #366	Medium	131	29	133	213	18
	DMSO	126	25	109	232	22
	S9 (RLA005)	178	40	131	409	37
	1-NP (1 μg)	485	749	139	279	60
	ICR-191 (1 μg)	2104				
	2-NF (5 μg)		418			
	NaN_3 (1 μg)			408		
	Cum. HPx (50 μg)				1312	
	2,4,7-TNF (0.25 μg)					975
	2-AF + S9 (10 μg)	390	915	347	478	921
INITIAL #367	Medium	101	23	104	239	27
	DMSO	96	29	103	232	19
	S9 (RLA005)	145	48	119	396	34
	1-NP (1 μg)	334	768	262	283	49
	ICR-191 (1 μg)	2153				
	2-NF (5 μg)		496			
	NaN_3 (1 μg)			430		
	Cum. HPx (50 μg)					
	2,4,7-TNF (0.25 μg)				1356	1027
	2-AF + S9 (10 μg)	381	818	373	513	641
REPEAT #367	Medium	113	27	139	241	22
	DMSO	115	24	124	222	18
	S9 (RLA005)	170	34	135	358	38
	1-NP (1 μg)	398	765	371	227	56
	ICR-191 (1 μg)	2115				
	2-NF (5 μg)		576			
	NaN_3 (1 μg)			498		
	Cum. HPx (50 μg)				1167	
	2,4,7-TNF (0.25 μg)					1008
	2-AF + S9 (10 μg)	408	1011	351	433	601

Table 1. continued

Controls		TA97A	TA98	TA100	TA102	TA98NR
INITIAL #368	Medium	90	17	111	239	17
	DMSO	89	19	120	232	11
	S9 (RLA005)	153	26	139	396	23
	1-NP (1 µg)	309	589	271	283	46
	ICR-191 (1 µg)	2105				
	2-NF (5 µg)		456			
	NaN_3 (1 µg)			541		
	Cum. HPx (50 µg)				1356	
	2,4,7-TNF (0.25 µg)					1196
	2-AF + S9 (10 µg)	420	790	297	513	714
REPEAT #368	Medium	116	25	112	243	27
	DMSO	86	22	102	237	19
	S9 (RLA005)	170	44	107	404	38
	1-NP (1 µg)	484	807	319	282	60
	ICR-191 (1 µg)	2016				
	2-NF (5 µg)		571			
	NaN_3 (1 µg)			550		
	Cum. HPx (50 µg)				1018	
	2,4,7-TNF (0.25 µg)					1361
	2-AF + S9 (10 µg)	463	838	348	538	693
INITIAL #369	Medium	112	24	114	233	51
	DMSO	106	26	104	231	56
	S9 (RLA005)	164	36	120	389	41
	1-NP (1 µg)	429	870	345	247	57
	ICR-191 (1 µg)	2167				
	2-NF (5 µg)		466			
	NaN_3 (1 µg)			597		
	Cum. HPx (50 µg)				913	
	2,4,7-TNF (0.25 µg)					1274
	2-AF + S9 (10 µg)	373	761	439	534	631
REPEAT #369	Medium	91	26	132	269	26
	DMSO	88	26	114	250	27
	S9 (RLA005)	124	41	132	427	42
	1-NP (1 µg)	361	964	319	241	62
	ICR-191 (1 µg)	1994				
	2-NF (5 µg)		581			
	NaN_3 (1 µg)			688		
	Cum. HPx (50 µg)				1195	
	2,4,7-TNF (0.25 µg)					1114
	2-AF + S9 (10 µg)	385	956	381	503	768

Table 1. continued

Controls		TA97A	TA98	TA100	TA102	TA98NR
INITIAL #568	Medium	115	37	138	209	25
	DMSO	93	28	121	214	21
	S9 (RLA005)	173	41	129	352	40
	1-NP (1 µg)	437	995	395	224	65
	ICR-191 (1 µg)	2037				
	2-NF (5 µg)		503			
	NaN$_3$ (1 µg)			543		
	Cum. HPx (50 µg)				917	
	2,4,7-TNF (0.25 µg)					1383
	2-AF + S9 (10 µg)	330	932	307	415	550
REPEAT #568	Medium	114	21	114	169	15
	DMSO	99	22	108	201	11
	S9 (RLA005)	147	26	131	379	23
	1-NP (1 µg)	434	868	136	258	94
	ICR-191 (1 µg)	1970				
	2-NF (5 µg)		527			
	NaN$_3$ (1 µg)			373		
	Cum. HPx (50 µg)				906	
	2,4,7-TNF (0.25 µg)					1379
	2-AF + S9 (10 µg)	304	612	348	443	376
INITIAL #580	Medium	92	30	103	169	20
	DMSO	99	22	112	201	20
	S9 (RLA005)	160	43	108	379	41
	1-NP (1 µg)	379	772	336	258	91
	ICR-191 (1 µg)	1930				
	2-NF (5 µg)		474			
	NaN$_3$ (1 µg)			545		
	Cum. HPx (50 µg)				906	
	2,4,7-TNF (0.25 µg)					1343
	2-AF + S9 (10 µg)	315	725	258	443	543
REPEAT #580	Medium	96	19	113	226	14
	DMSO	99	19	120	209	11
	S9 (RLA005)	139	22	129	237	22
	1-NP (1 µg)	369	844	109	229	85
	ICR-191 (1 µg)	1862				
	2-NF (5 µg)		464			
	NaN$_3$ (1 µg)			357		
	Cum. HPx (50 µg)				760	
	2,4,7-TNF (0.25 µg)					1425
	2-AF + S9 (10 µg)	348	723	363	401	419

Table 1. continued

Controls		TA97A	TA98	TA100	TA102	TA98NR
INITIAL #626	Medium	123	29	116	231	16
	DMSO	98	28	114	223	22
	S9 (RLA005)	176	42	131	395	38
	1-NP (1 μg)	417	941	170	215	73
	ICR-191 (1 μg)	1965				
	2-NF (5 μg)		533			
	NaN_3 (1 μg)			437		
	Cum. HPx (50 μg)				809	
	2,4,7-TNF (0.25 μg)					1581
	2-AF + S9 (10 μg)	358	848	307	473	788
REPEAT #626	Medium	92	22	117	221	19
	DMSO	98	15	106	221	17
	S9 (RLA005)	137	28	138	356	28
	1-NP (1 μg)	424	1017	154	241	71
	ICR-191 (1 μg)	1991				
	2-NF (5 μg)		435			
	NaN_3 (1 μg)			368		
	Cum. HPx (50 μg)				836	
	2,4,7-TNF (0.25 μg)					1647
	2-AF + S9 (10 μg)	486	902	434	445	560

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[a] Difficulties with tester strain TA102 necessitated repeating the analysis with some samples. Therefore, the positive and negative controls are identical for the following samples: #366 (initial), #367 (initial), and #368 (initial); and #568 (repeat) and #580 (initial).

[b] 1-NP, 1-nitropyrene

[c] 2-NF, 2-nitrofluorene

[d] Cum HPx, cumene hydroperoxide

[e] 2,4,7-TNF, 2,4,7-trinitro-9-fluorenone

[f] 2-AF, 2-aminofluorene

Table 2. Cumulative Controls for Tester Strains (HIS^+ REVERTANTS)

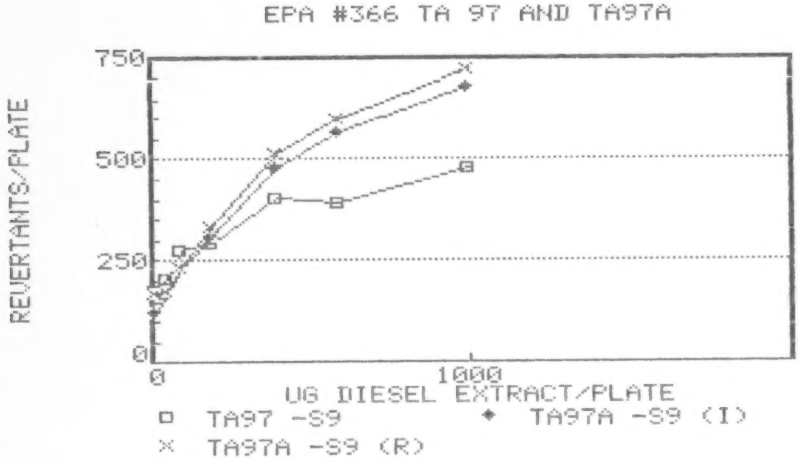
Treatment		TA97A	TA98	TA100	TA102	TA98NR
MEDIUM	Number	14	14	14	11	14
	Mean	105.7	24.7	117.7	226.7	22.3
	Std. Dev.	13.7	5.7	13.0	25.0	9.3
	Std. Error	3.7	1.7	3.3	7.7	2.7
	Minimum	90	16	100	169	14
	Maximum	131	37	139	269	51
DMSO	Number	14	14	14	11	11
	Mean	99.0	22.7	110.7	224.7	20.7
	Std. Dev.	10.7	4.7	8.7	13.7	11.3
	Std. Error	3.0	1.3	2.3	4.0	3.0
	Minimum	86	14	94	201	11
	Maximum	126	29	124	250	56
S9 (RLA005)	Number	14	14	14	11	14
	Mean	157.3	35.3	125.0	373.0	33.0
	Std. Dev.	16.7	8.7	12.3	51.0	8.3
	Std. Error	4.3	2.3	3.3	15.3	2.3
	Minimum	124	22	100	237	19
	Maximum	178	48	139	427	42
1-NITROPYRENE	Number	141	14	14	11	14
	Mean	407.0	822.0	247.0	247.7	65.3
	Std. Dev.	51.7	137.0	102.7	24.7	15.7
	Std. Error	12.7	36.7	27.3	7.3	4.3
	Minimum	309	561	109	215	45
	Maximum	485	1017	395	283	94
2-AMINOFLUORENE +S9	Number	14	14	14	11	14
	Mean	381.7	826.3	353.7	470.7	640.3
	Std. Dev.	51.7	109.7	51.0	47.0	147.7
	Std. Error	13.7	29.3	13.7	14.3	39.7
	Minimum	104	612	258	401	376
	Maximum	486	1011	439	538	921

	ICR-191 TA97A	2-NF TA98	NaN_3 TA100	Cum. HPx TA102	2,4,7-TNF TA98NR
Number	14	14	14	11	14
Mean	2035.7	497.3	476.7	1017.3	1262.7
Std. Dev.	89.7	53.0	104.7	207.7	221.3
Std. Error	24.0	14.0	28.0	62.7	59.3
Minimum	1862	418	339	760	966
Maximum	2167	581	688	1356	1647

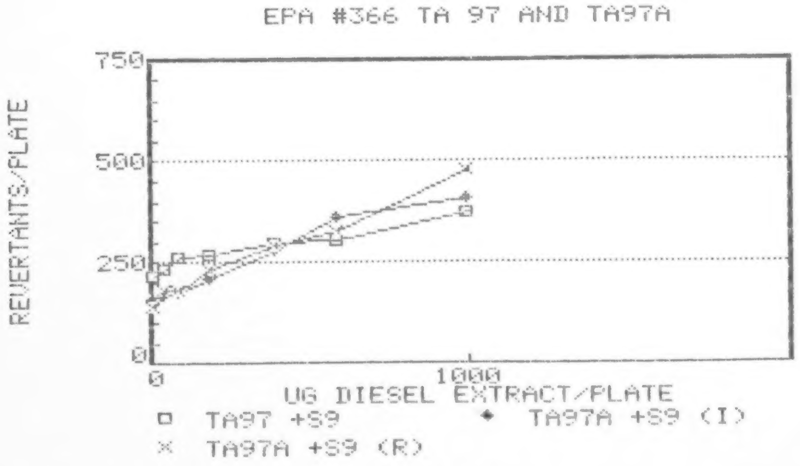
Table 3. His$^+$ Revertants/µg Extract

Sample Identification	S9	TA97A	TA98	TA100	TA102	TA98NR
#366 - Initial	-	1.263	0.298	1.508	0.413	0.278
	+	0.349	0.292	0.665	0.260	0.161
Repeat	-	0.971	0.355	1.611	0.688	0.267
	+	0.483	0.260	0.566	0.388	0.142
#367 - Initial	-	0.962	0.339	1.750	0.799	0.364
	+	1.675	1.205	2.032	0.990	1.077
Repeat	-	1.299	0.630	1.523	0.554	0.344
	+	1.813	1.510	2.375	0.720	0.851
#368 - Initial	-	1.575	0.628	1.788	0.611	0.508
	+	1.385	0.893	2.097	0.438	0.646
Repeat	-	1.675	0.528	2.963	0.655	0.588
	+	1.147	1.054	1.162	0.527	0.566
#369 - Initial	-	1.625	0.576	1.575	0.374	0.358
	+	2.175	1.322	1.282	0.781	0.907
Repeat	-	1.313	0.519	1.678	0.458	0.377
	+	2.063	1.293	1.425	0.733	1.080
#626 - Initial	-	0.664	0.321	0.728	0.500	0.254
	+	0.316	0.264	0.808	1.013	0.180
Repeat	-	0.615	0.235	0.677	0.250	0.181
	+	0.606	0.399	0.691	0.390	0.131
#568 - Initial	-	3.025	0.963	2.225	0.725	0.626
	+	0.790	0.784	1.041	0.470	0.387
Repeat	-	2.363	0.992	0.761	0.259	0.551
	+	0.641	0.720	2.663	0.700	0.313
#580 - Initial	-	0.981	0.348	1.093	0.225	0.190
	+	0.632	0.539	0.596	0.187	0.231
Repeat	-	0.780	0.399	1.017	0.107	0.188
	+	0.338	0.623	0.709	0.369	0.296

A. µg CH_2Cl_2 Extract	TA97 -S9	TA97A -S9 (I)	TA97A -S9 (R)
20	178	126	173
60	206	166	177
100	274	227	233
200	296 *	313 *	337
400	404 *	481 *	513 *
600	392 *	564 *	602 *
1000	480 *	683 *	726 *



B. µg CH_2Cl_2 Extract	TA97 +S9	TA97A +S9 (I)	TA97A +S9 (R)
20	217	161	144
60	235	170	182
100	267	177	186
200	270 *	213	237
400	300 *	280	291 *
600	304 *	362	328 *
1000	375 *	411 *	482 *



*Denotes points omitted from linear regression analysis

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Figure 2

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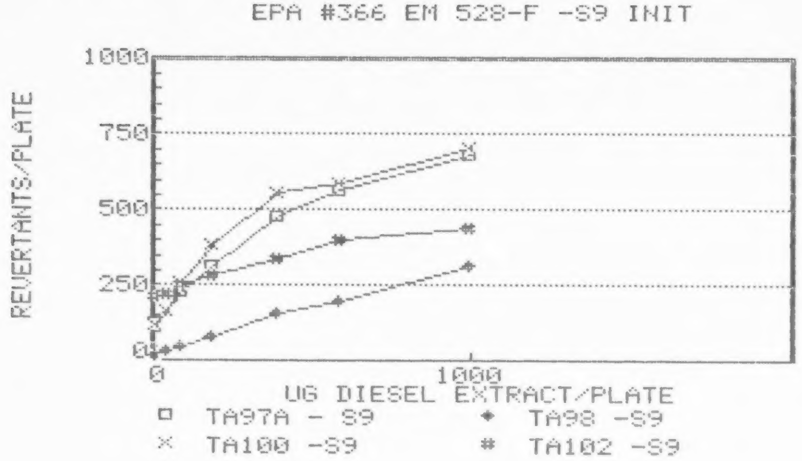
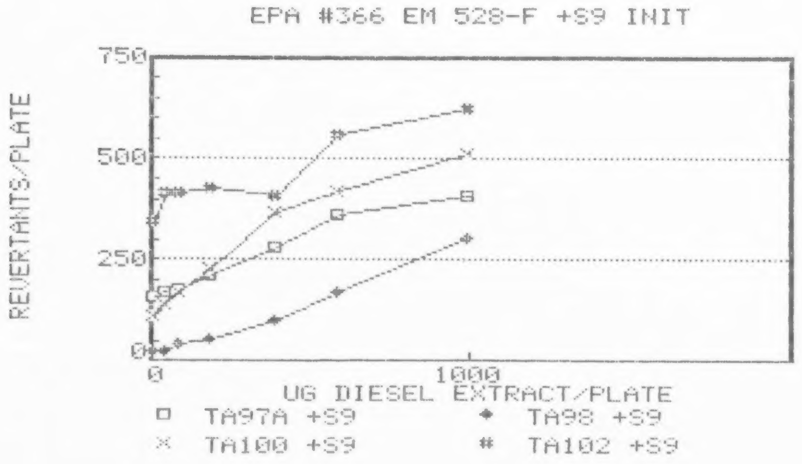
μg CH_2Cl_2 Extract	TA97A - S9	TA98 -S9	TA100 -S9	TA102 -S9
20	126	23	123	212
60	166	34	170	220
100	227	47	265	256
200	313*	82	389	283
400	481*	158	557*	337*
600	564*	199	590*	402*
1000	683*	313	704*	443*



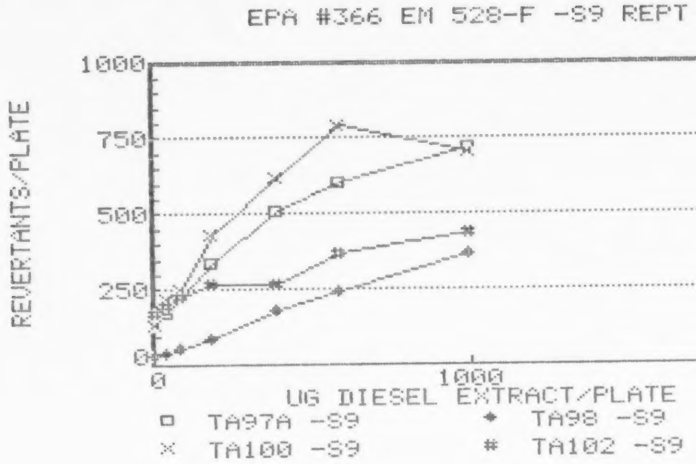
B.

μg CH_2Cl_2 Extract	TA97A +S9	TA98 +S9	TA100 +S9	TA102 +S9
20	161	27*	116	346
60	170	29	143	415
100	177	41	171	415
200	213	58	227	427
400	280	99	371	411
600	362	170	422*	559
1000	411*	306	512*	624*



A.

µg CH_2Cl_2 Extract	TA97A -S9	TA98 -S9	TA100 -S9	TA102 -S9
20	173	36	138	178
60	177	46	224	197
100	233	57	251	233
200	337	86	436	268 *
400	513 *	180	624 *	271 *
600	602 *	249	792 *	371 *
1000	726 *	373	706 *	441 *



B.

µg CH_2Cl_2 Extract	TA97A +S9	TA98 +S9	TA100 +S9	TA102 +S9
20	144	39	131 *	405
60	182	47	139	414
100	186	57	160	436
200	237	72	242	429 *
400	291 *	145	324	475 *
600	328 *	195	452	543 *
1000	482 *	286	560 *	559 *

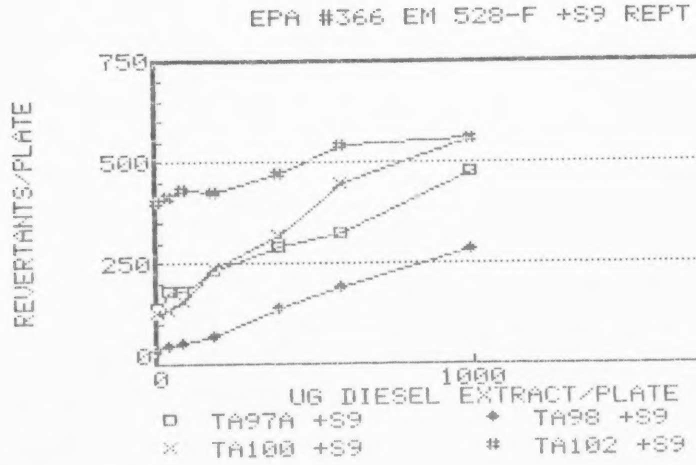


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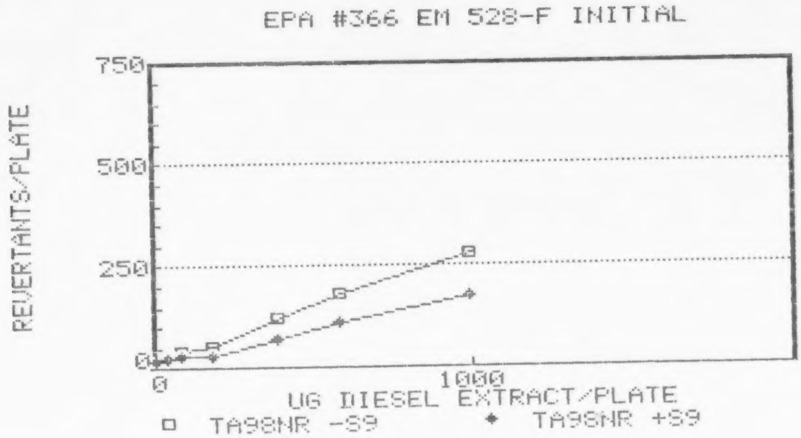
Figure 4

A.

μg CH_2Cl_2 Extract	TA98NR -S9	TA98NR +S9
20	16	19
60	25	28
100	44	30
200	56	34
400	127	72
600	186	111
1000	284	175



B.

μg CH_2Cl_2 Extract	TA98NR -S9	TA98NR +S9
20	20	32
60	36	41
100	42	40
200	75	50
400	96	79
600	178	94
1000	287	178

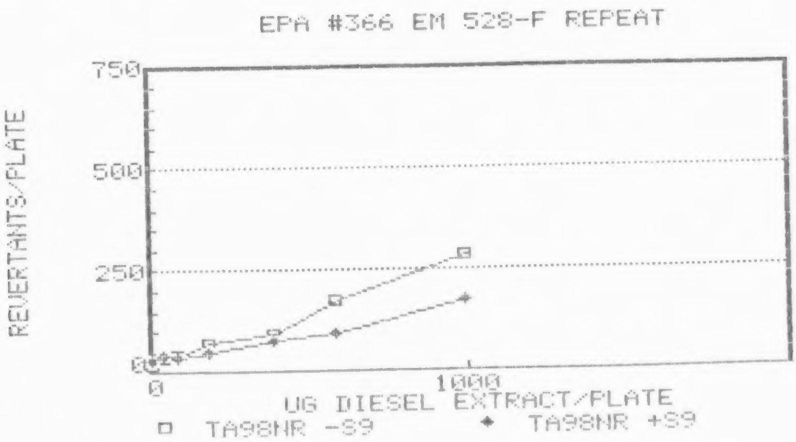
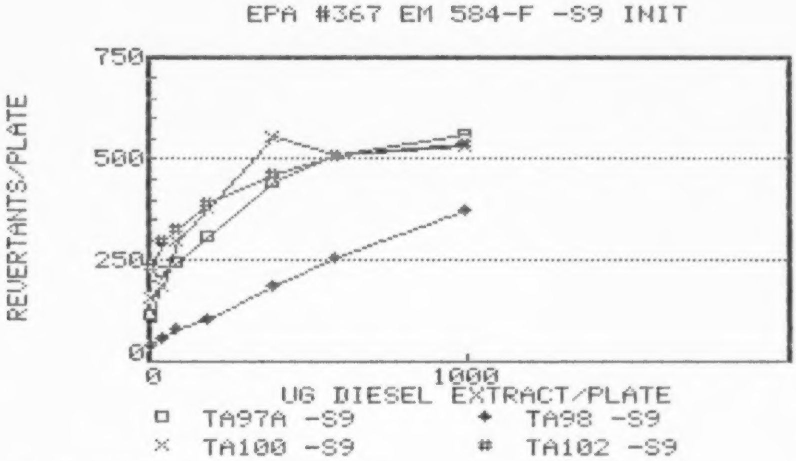


Figure 5

A.

µg CH_2Cl_2 Extract	TA97A -S9	TA98 -S9	TA100 -S9	TA102 -S9
20	122	45	158	238
60	221	62	190	298
100	249	85	298	326
200	313	106	382 *	390
400	446 *	188	557 *	461 *
600	508 *	259	509 *	510 *
1000	562 *	375	533 *	536 *



B.

µg CH_2Cl_2 Extract	TA97A +S9	TA98 +S9	TA100 +S9	TA102 +S9
20	161	52	163	388
60	248	88	233	437
100	295	134	409	494
200	412 *	273	521	568
400	596 *	501	750 *	679 *
600	637 *	584 *	790 *	799 *
1000	712 *	737 *	903 *	895 *

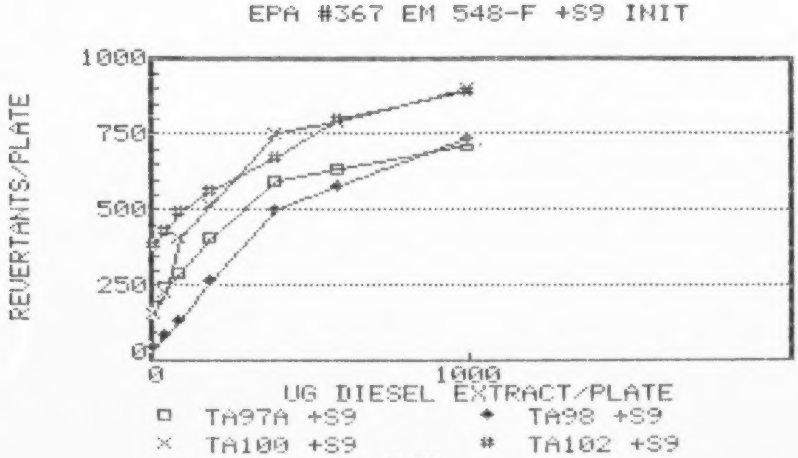
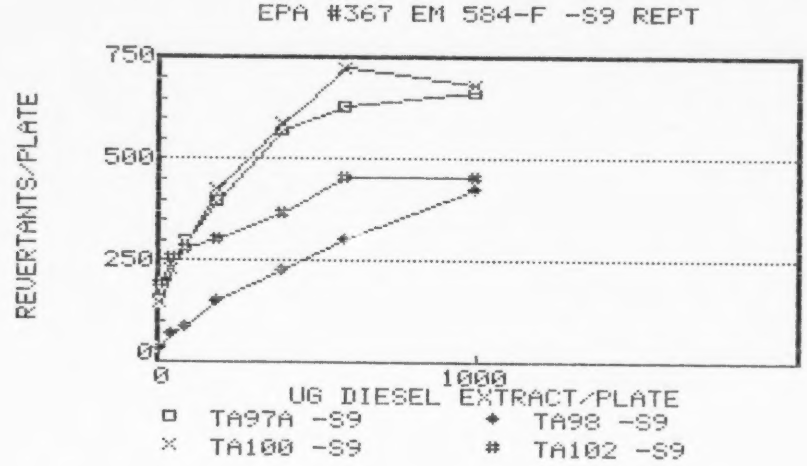


Figure 6

A. μg CH_2Cl_2 Extract	TA97A -S9	TA98 -S9	TA100 -S9	TA102 -S9
20	156	39	149	196
60	247	72	231	261
100	298	91	296	283
200	401	155	429	308
400	573 *	228 *	588 *	369 *
600	630 *	307 *	725 *	458 *
1000	667 *	425 *	681 *	458 *



B. μg CH_2Cl_2 Extract	TA97A +S9	TA98 +S9	TA100 +S9	TA102 +S9
20	162	51	156	370
60	253	94	229	439
100	307	150	346	450
200	407 *	318	425 *	512
400	551 *	471 *	613 *	607 *
600	659 *	588 *	729 *	654 *
1000	771 *	726 *	810 *	661 *

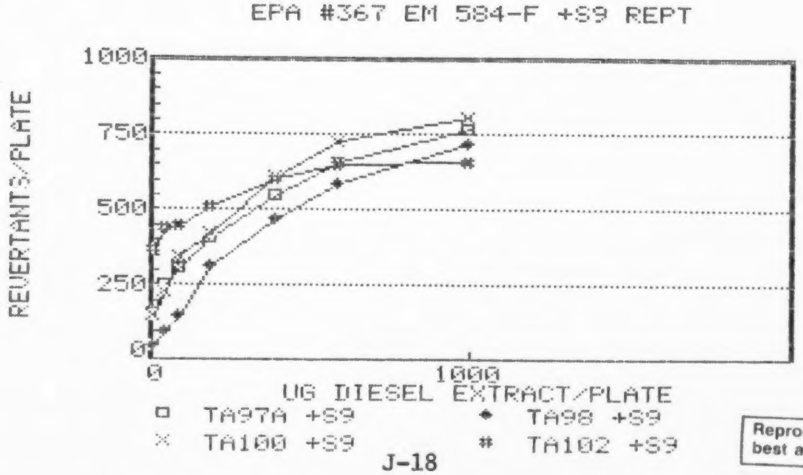


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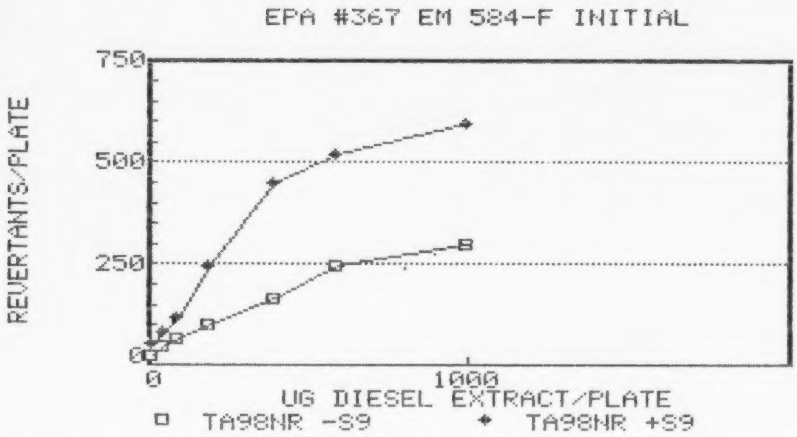
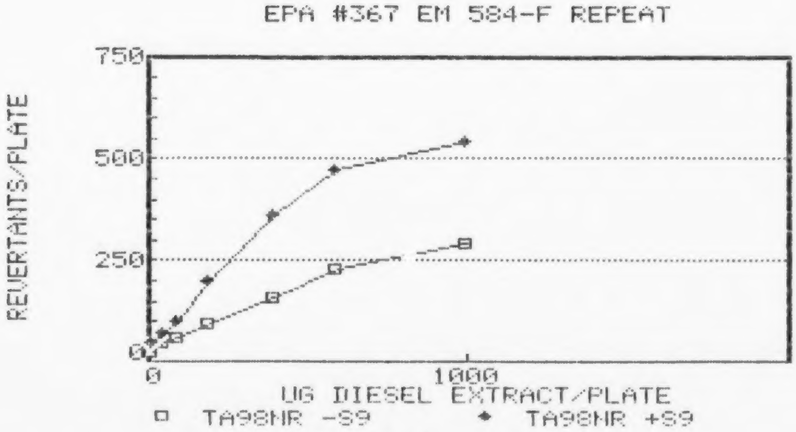
Figure 7

A. μg CH_2Cl_2 Extract	TA98NR -S9	TA98NR +S9
20	24	55
60	51	82
100	69	117
200	100	245
400	168	453
600	245	521 *
1000	299 *	598 *



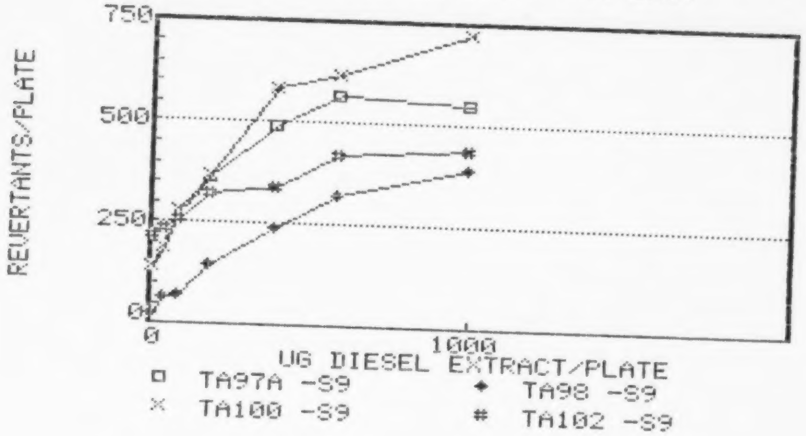
B. μg CH_2Cl_2 Extract	TA98NR -S9	TA98NR +S9
20	27	47
60	49	73
100	63	99
200	94	203
400	161	363
600	232	474 *
1000	291 *	541 *



A.

μg CH_2Cl_2 Extract	TA97A -S9	TA98 -S9	TA100 -S9	TA102 -S9
20	143	29	140	217
60	214	65	190	235
100	269	72	283	261
200	362	146	368	325
400	492	244	587	341
600	567	322	622	421
1000	551	395	723	438

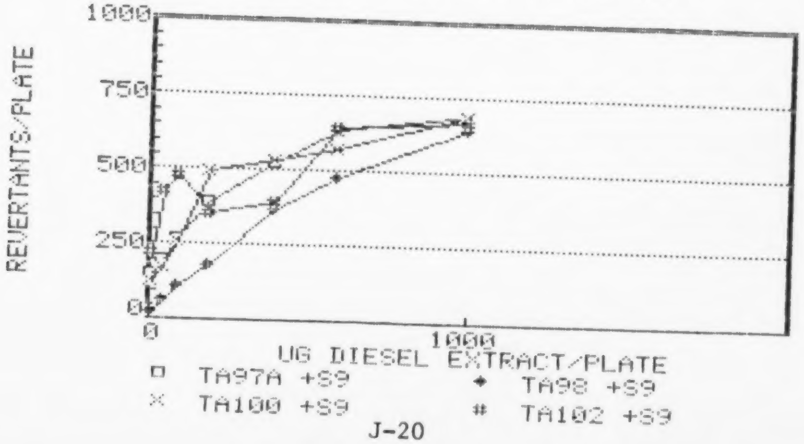
EPA #368 EM 586-F -S9 INIT



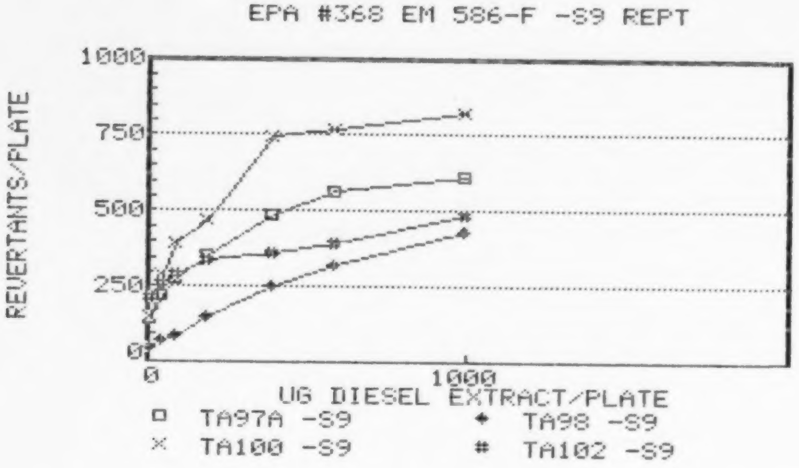
B.

μg CH_2Cl_2 Extract	TA97A +S9	TA98 +S9	TA100 +S9	TA102 +S9
20	150	31	128	223
60	200	65	179	427
100	271	111	263	479
200	397	185	496	353
400	525	373	537	392
600	634	482	572	643
1000	691	641	694	669

EPA #368 EM 568-F +S9 INIT



A. μg CH_2Cl_2 Extract	TA97A -S9	TA98 -S9	TA100 -S9	TA102 -S9
20	147	53	156	218
60	219	77	292	260
100	281	93	393	296
200	355	150	476	340
400	486	254	749	365
600	565	325	768	393
1000	611	437	825	487



B. μg CH_2Cl_2 Extract	TA97A +S9	TA98 +S9	TA100 +S9	TA102 +S9
20	175	58	142	387
60	235	104	206	434
100	292	141	263	462
200	385	249	361	489
400	503	409	611	522
600	568	525	822	562
1000	752	773	880	595

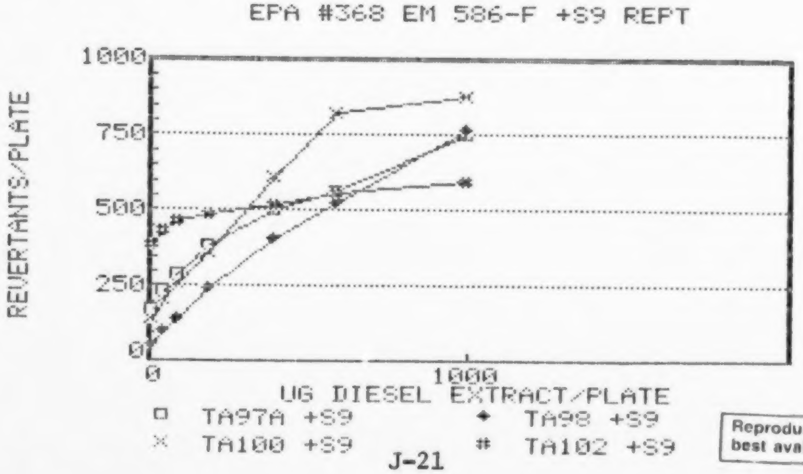


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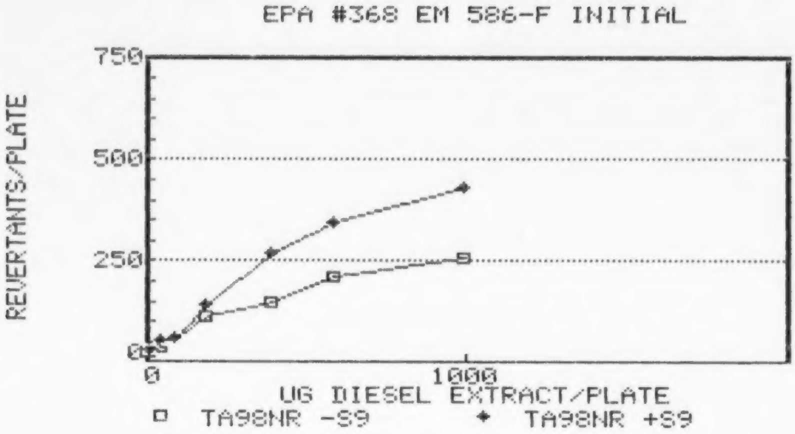
Figure 10

A.

µg CH_2Cl_2 Extract	TA98NR -S9	TA98NR +S9
20	27	31
60	36	56
100	61	60
200	115	141
400	150*	272
600	213*	347*
1000	261*	433*



B.

µg CH_2Cl_2 Extract	TA98NR -S9	TA98NR +S9
20	30	43
60	54	66
100	77	84
200	136	135
400	172 *	259
600	225 *	331 *
1000	298 *	472 *

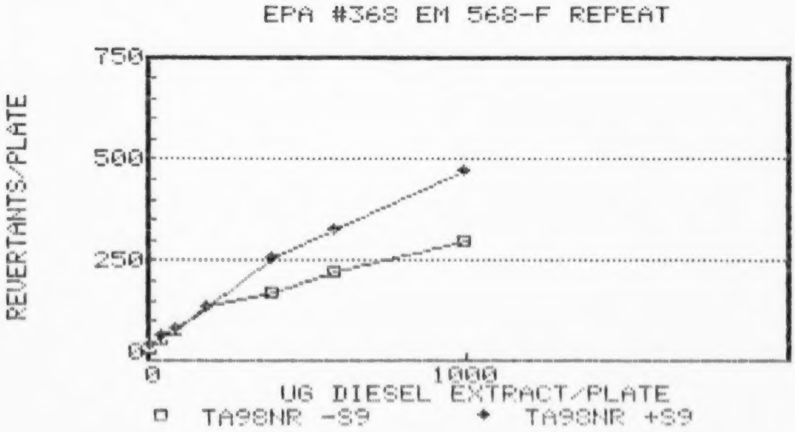
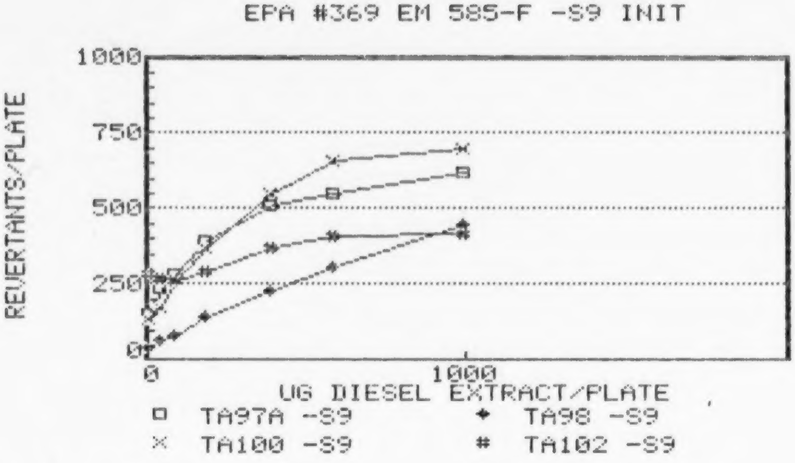


Figure 11

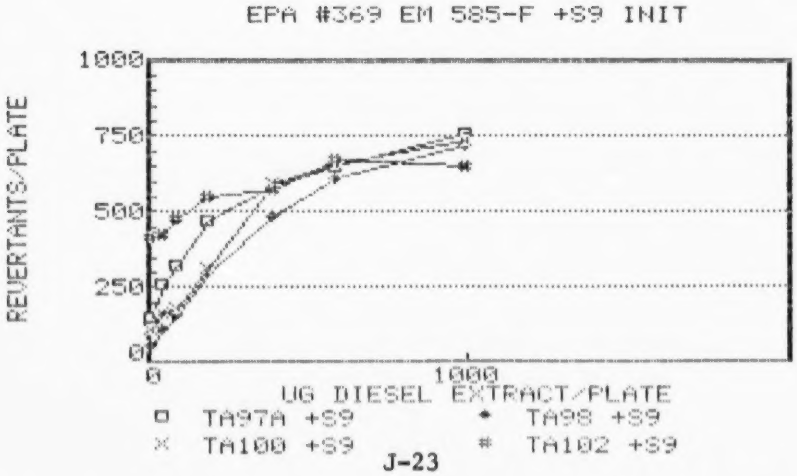
A.

µg CH_2Cl_2 Extract	TA97A -S9	TA98 -S9	TA100 -S9	TA102 -S9
20	153	40	135	283 *
60	235	69	178	272 *
100	283	80	261	261
200	391 *	146	371 *	292
400	513 *	228 *	552 *	372
600	553 *	306 *	658 *	408 *
1000	621 *	447 *	702 *	417 *



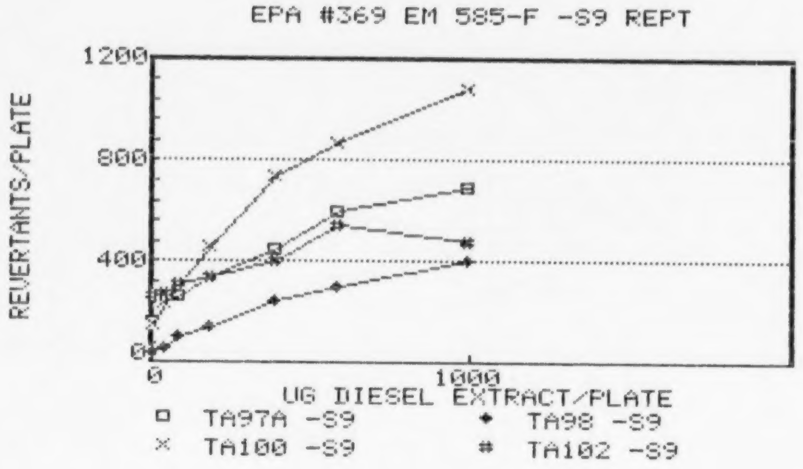
B.

µg CH_2Cl_2 Extract	TA97A +S9	TA98 +S9	TA100 +S9	TA102 +S9
20	153	59	114	420
60	263	117	171	425
100	327	159	185	478
200	473 *	299	318	552
400	589 *	485 *	601	575 *
600	655 *	610 *	663 *	678 *
1000	763 *	724 *	741 *	656 *



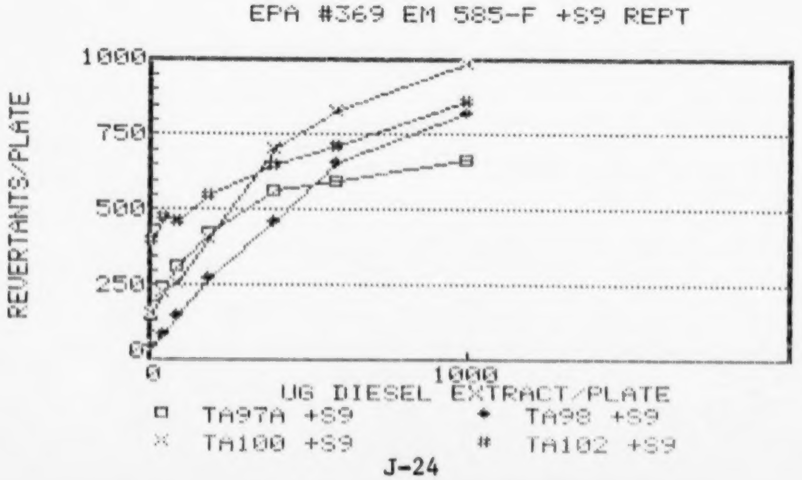
A.

µg CH_2Cl_2 Extract	TA97A -S9	TA98 -S9	TA100 -S9	TA102 -S9
20	163	42	157	262
60	239	63	236	275
100	268	104	312	309
200	337 *	146	462	340
400	449 *	242	737 *	409
600	596 *	298 *	869 *	541
1000	694 *	407 *	1086 *	475 *

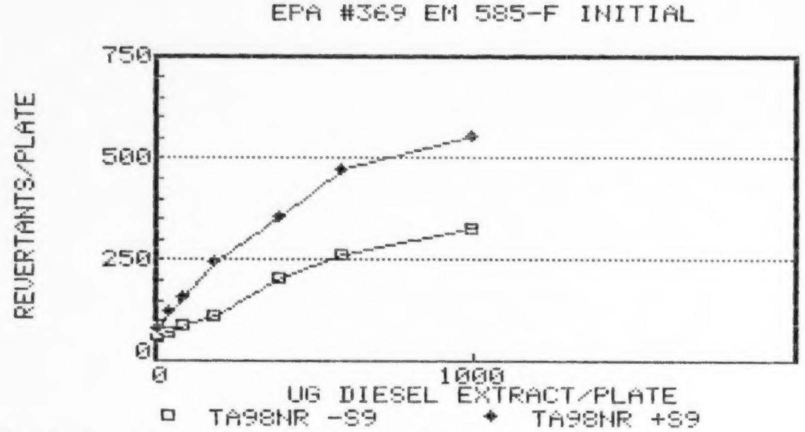


B.

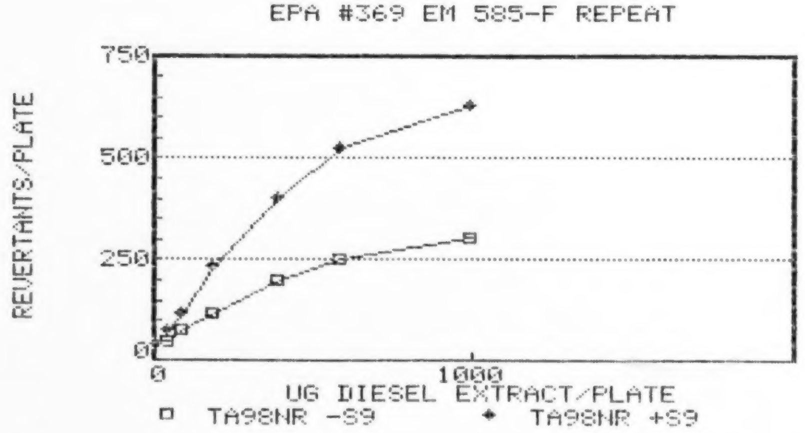
µg CH_2Cl_2 Extract	TA97A +S9	TA98 +S9	TA100 +S9	TA102 +S9
20	154	50	161	400
60	246	93	231	481
100	319	151	263	463
200	429 *	280	411	549
400	570 *	465 *	706	652 *
600	594 *	660 *	829 *	715 *
1000	668 *	822 *	986 *	861 *



A.	TA98NR -S9	TA98NR +S9
µg CH_2Cl_2 Extract		
20	64	85
60	73	124
100	90	162
200	115	249
400	205	355 *
600	265	471 *
1000	327 *	558 *



B.		
µg CH_2Cl_2 Extract	TA98NR -S9	TA98NR +S9
20	41	46
60	52	80
100	76	119
200	118	238
400	198	404 *
600	254	528 *
1000	303 *	632 *



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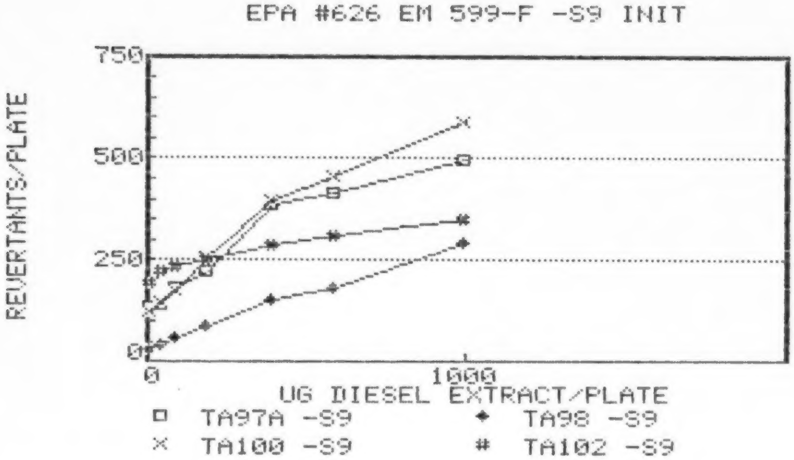
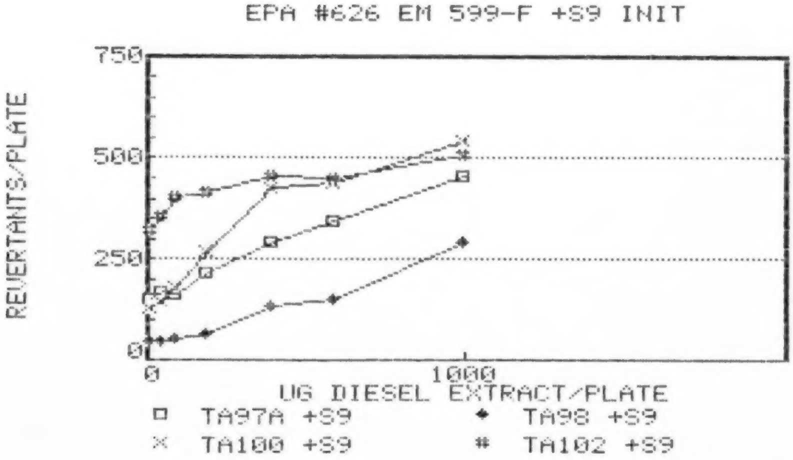
A.

µg CH_2Cl_2 Extract	TA97A -S9	TA98 -S9	TA100 -S9	TA102 -S9
20	135	32	123	195
60	140	45	151	225
100	186	62	180	235
200	223	90	259	255 ✓
400	384	155	398	287 ✓
600	415 ✓	181 ✓	454 ✓	312 ✓
1000	499 ✓	295 ✓	593 ✓	353 ✓



B.

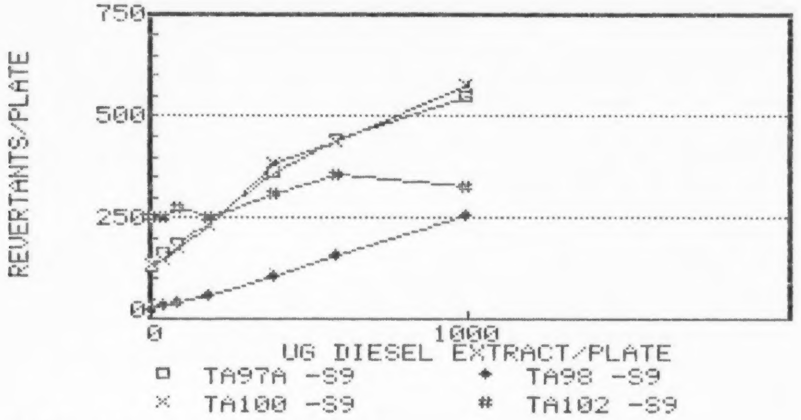
µg CH_2Cl_2 Extract	TA97A +S9	TA98 +S9	TA100 +S9	TA102 +S9
20	156 ✓	48 ✓	128	321
60	171 ✓	52 ✓	150	355
100	168	55	182	402
200	217	69	270	413 ✓
400	291	136	429	458 ✓
600	348	155	438 ✓	453 ✓
1000	458	295	545 ✓	509 ✓



A.

µg CH_2Cl_2 Extract	TA97A -S9	TA98 -S9	TA100 -S9	TA102 -S9
20	133	28	134	252*
60	166	38	147	252*
100	191	44	175	278*
200	246	60	237	255
400	364*	107	386	310
600	445*	158	438*	355
1000	547*	259	576*	331*

EPA #626 EM 599-F -S9 REPT



B.

µg CH_2Cl_2 Extract	TA97A +S9	TA98 +S9	TA100 +S9	TA102 +S9
20	156*	34*	135	346*
60	149	36	158	368*
100	165	47	174	354*
200	224	66	260	353
400	352	139	392	436
600	401*	233	401*	509
1000	458*	407	522*	554*

EPA #626 EM 599-F +S9 REPT

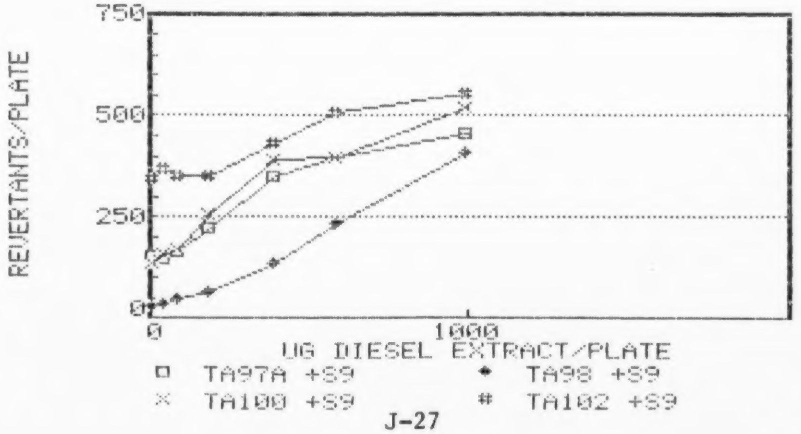
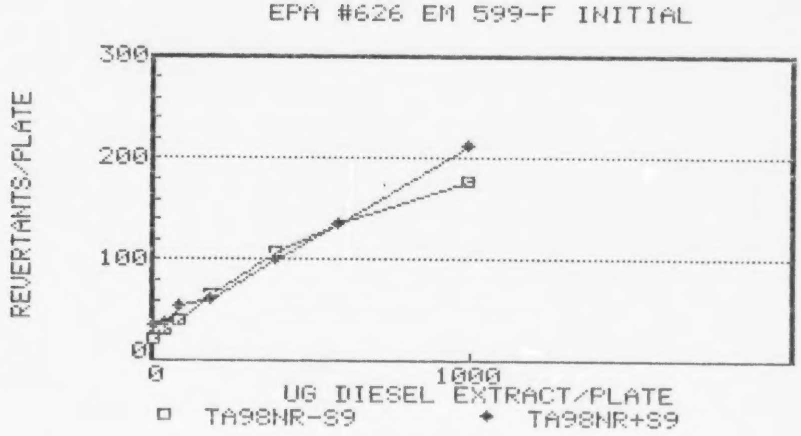


Figure 16

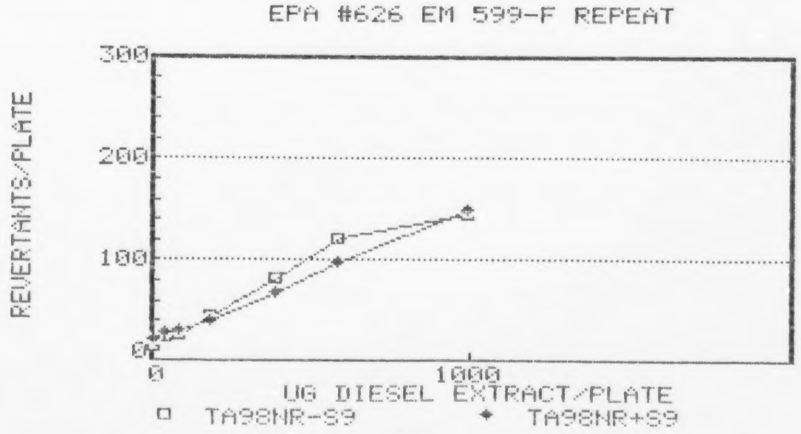
A.

µg CH_2Cl_2 Extract	TA98NR-S9	TA98NR+S9
20	21	36
60	32	39
100	40	54
200	67	62
400	108 *	102
600	135 *	135
1000	179 *	213



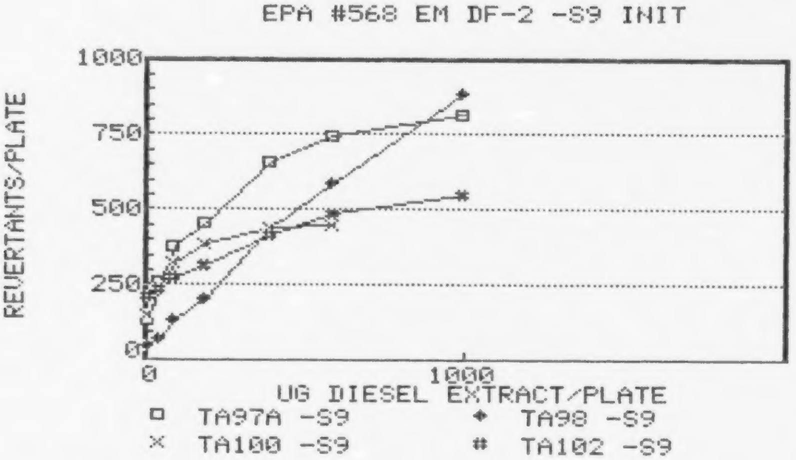
B.

µg CH_2Cl_2 Extract	TA98NR-S9	TA98NR+S9
20	15	23
60	25	30
100	26	32
200	46	40
400	82	68
600	121	99
1000	146 *	151



A.

µg CH_2Cl_2 Extract	TA97A -S9	TA98 -S9	TA100 -S9	TA102 -S9
20	134	51	150	218
60	264	71	247	241
100	376	135	328	276
200	457 *	205	389 *	316 *
400	658 *	443	443 *	421 *
600	748 *	590	449 *	487 *
1000	820 *	886 *		549 *



B.

µg CH_2Cl_2 Extract	TA97A +S9	TA98 +S9	TA100 +S9	TA102 +S9
20	164	51 *	156	381
60	175	67 *	196	427
100	240	90 *	286	432
200	301	140	359	474
400	460	288	559	532 *
600	561 *	445	614 *	567 *
1000	727 *	765	809 *	635 *

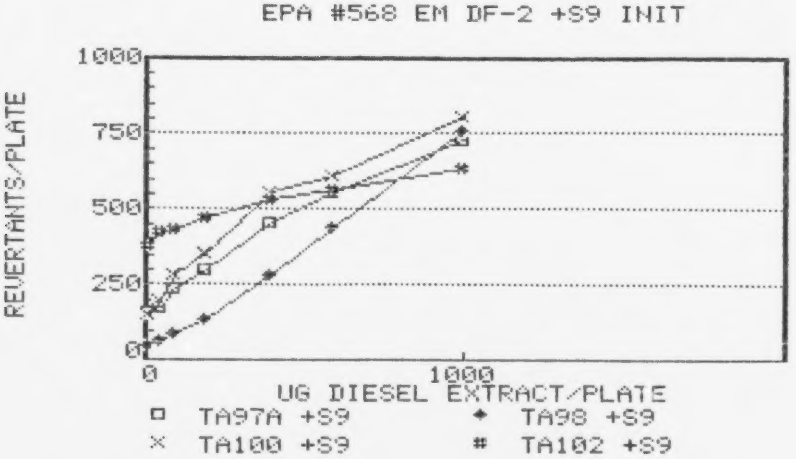
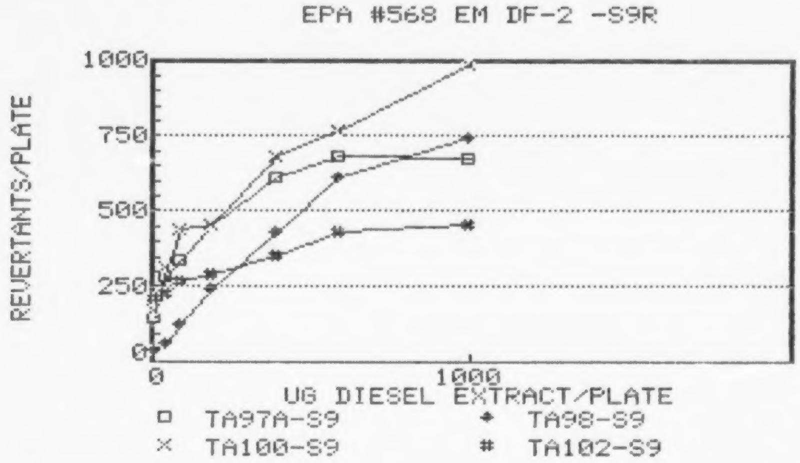


Figure 18

A.

µg CH_2Cl_2 Extract	TA97A-S9	TA98-S9	TA100-S9	TA102-S9
20	152	40	172	217
60	283	68	314	232
100	341	130	439	266
200	458 ✓	244	454	290
400	610 ✓	430	681	357
600	683 ✓	610	769	431
1000	679 ✓	747 ✓	990	460



B.

µg CH_2Cl_2 Extract	TA97A+S9	TA98+S9	TA100+S9	TA102+S9
20	181	40	146	367
60	268	55	282	383
100	381	85	359	423
200	563	171	424 ✓	423 ✓
400	765	326	628 ✓	454 ✓
600	786	444	393 ✓	437 ✓
1000	823	740	465 ✓	507 ✓

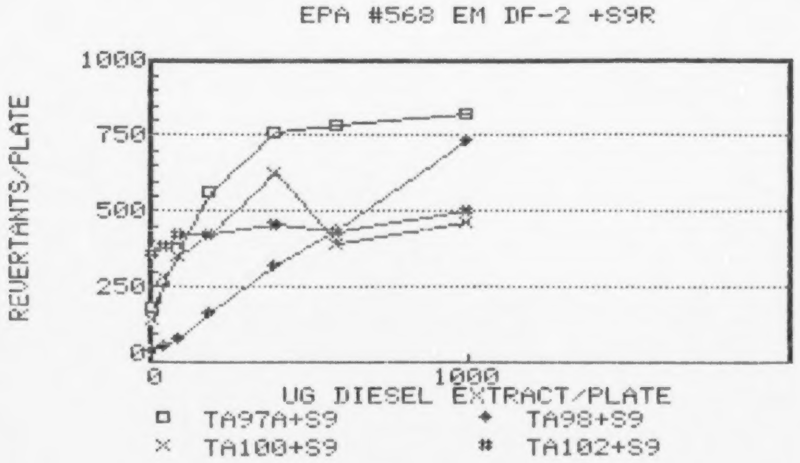
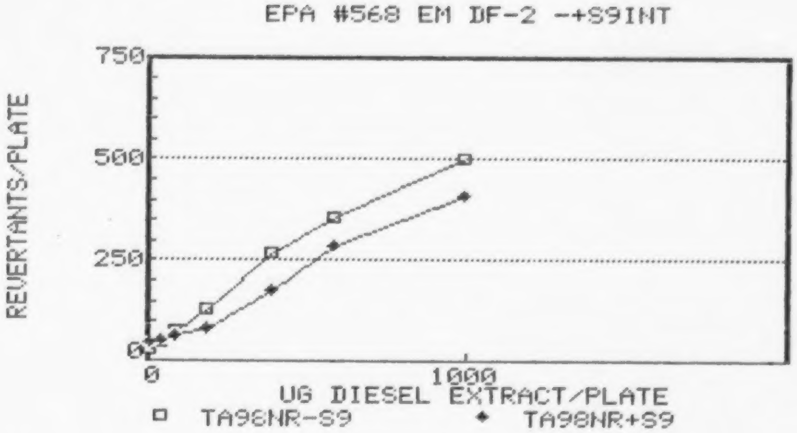
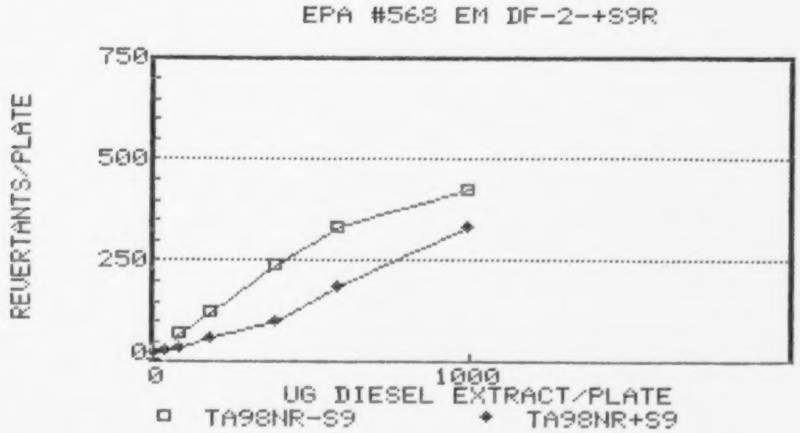


Figure 1[illegible]

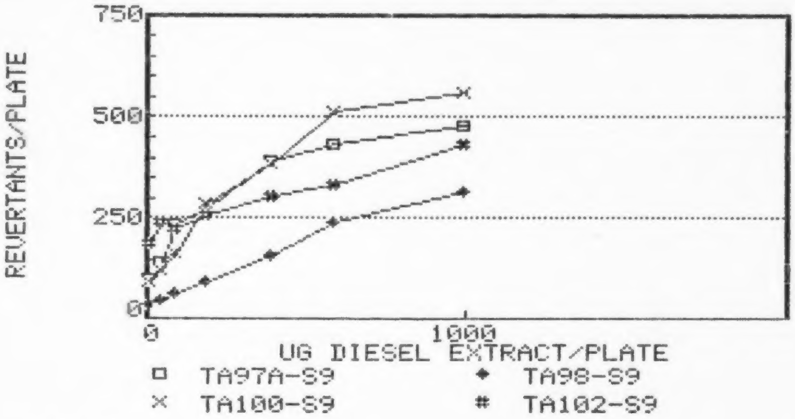
A. µg CH_2Cl_2 Extract	TA98NR-S9	TA98NR+S9
20	31	48
60	51	53
100	78	67
200	133	87
400	268	177
600	355 *	286
1000	503 *	408



B. µg CH_2Cl_2 Extract	TA98NR-S9	TA98NR+S9
20	23	27
60	32	32
100	75	35
200	127	60
400	243	100
600	335	187
1000	427 *	332



A. µg CH_2Cl_2 Extract	TA97A-S9	TA98-S9	TA100-S9	TA102-S9
20	102	37	97	190
60	141	51	124	240
100	233	65	167	225
200	276	97	289	258
400	392 *	160	386 *	305
600	431 *	243	517 *	336
1000	481 *	314 *	560 *	431


EPA #580 EM 600-F-S9I

B. µg CH_2Cl_2 Extract	TA97A+S9	TA98+S9	TA100+S9	TA102+S9
20	144	45	101	352 *
60	160	62	132	405
100	177	85	155	417
200	267	119	217	455
400	375	238	330	473
600	400 *	358	394 *	513
1000	475 *	491 *	582 *	588

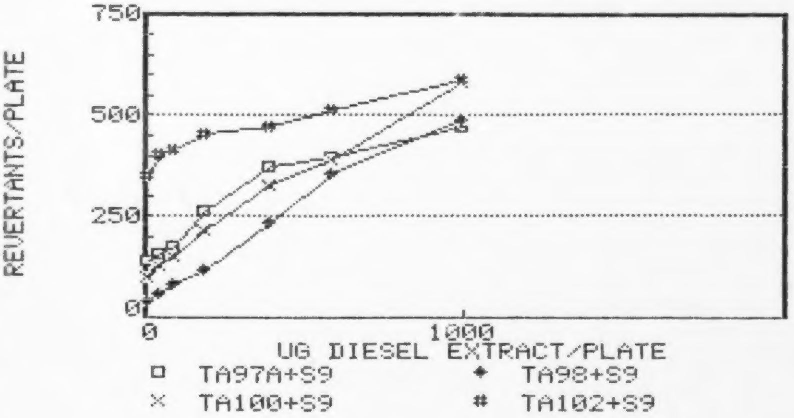

EPA #580 EM 600-F+S9I

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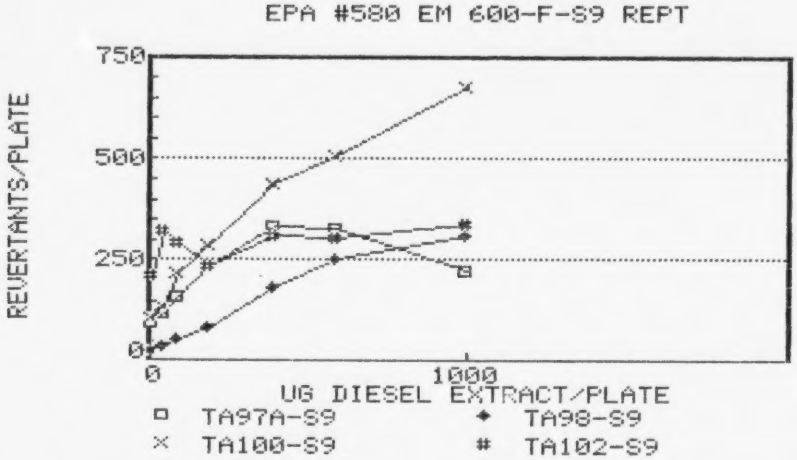
Figure 21

A. µg CH_2Cl_2 Extract	TA97A-S9	TA98-S9	TA100-S9	TA102-S9
20	97	24	109	211
60	118	39	135	321
100	159	57	216	292
200	234	85	286	236
400	335 *	183	441 *	309
600	329 *	251	506 *	308 *
1000	223 *	309 *	677 *	338 *



B. µg CH_2Cl_2 Extract	TA97A+S9	TA98+S9	TA100+S9	TA102+S9
20	124 *	23	103	305
60	128	32	121	367
100	168	69	165	438
200	258	104	227	374
400	423	262	318 *	487
600	411	372	370 *	508 *
1000	449	564 *	428 *	541 *

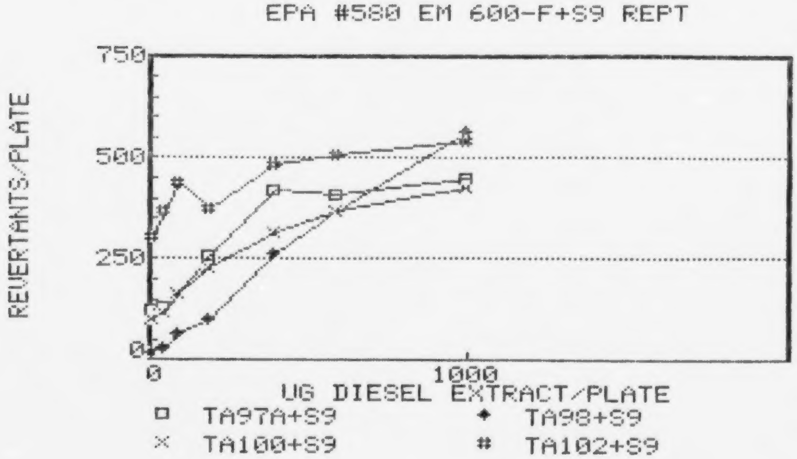
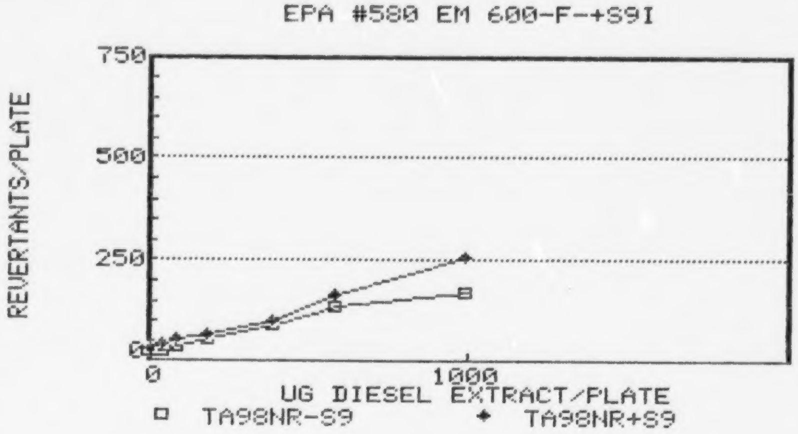
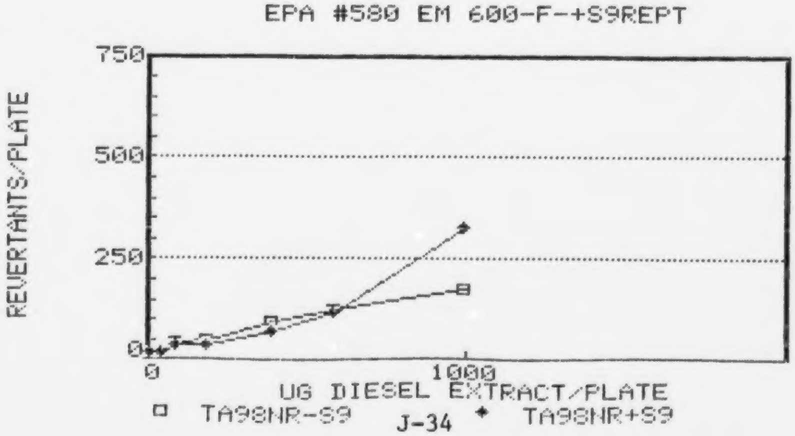


Figure 22

A. μg CH_2Cl_2 Extract	TA98NR-S9	TA98NR+S9
20	25 *	33
60	29	43
100	40	54
200	55	65
400	92	104
600	134	167
1000	173 *	260



B. μg CH_2Cl_2 Extract	TA98NR-S9	TA98NR+S9
20	15 *	23
60	20	19
100	42	36
200	52	36
400	98	74
600	125	121
1000	175 *	328



UNIVERSITY OF CALIFORNIA, BERKELEY

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DEPARTMENT OF BIOCHEMISTRY BERKELEY, CALIFORNIA 94720

April 5, 1984

Dear Colleague:

We have received numerous complaints regarding the growth properties of the standard tester strain, TA97. These include low levels of viability of overnight cultures, faint background growth, and pin-point colonies on mutagenesis plates. We think these problems are due to the *uvrB* deletion, and therefore we have reconstructed the strain. The reconstructed strain is designated TA97a. It has improved growth properties compared to the original TA97. Its response to the mutagens ICR-191, dexon, and 2-aminofluorene is identical to that of TA97. We suggest that TA97a be used in general mutagenicity screening in place of TA97, and we are now sending it out routinely.

In the Revised Methods paper (Maron and Ames, *Mutation Research 113*, 173-215, 1983) we recommended mitomycin C as the positive control for TA102. Recently, however, David Levin has discovered that mitomycin C causes extragenic suppressor mutations. Suppressors are slow growers, accounting for the pin-point colonies on MMC plates. Incubating the plates longer than 48 hours is not recommended. Because of the problem with suppressors, we suggest using cumene hydroperoxide as the positive control for TA102. It is commercially available (Pfaltz and Bauer) and does not require metabolic activation. Please see Levin *et al.* (1982), *PNAS*, *79*, 7445-7449. The dose-response curve for cumene hydroperoxide with TA102 is shown on page 7447. Danthron, an anthracene quinone (available from Sigma) can be used as a positive control requiring S9 activation (1,140 revertants per 30 µg using 50 µl S9 per plate in the preincubation assay). See Levin *et al.* (1983) Detection of Oxidative Mutagens in a New *Salmonella* Tester Strain (TA102), *Methods in Enzymology*, in press.

When you receive TA102 from our laboratory, or when you reisolate from your frozen master copy, you may need to test a larger number of isolates than usual (perhaps 10) to find one with an acceptable spontaneous reversion frequency. Patch the isolates onto an ampicillin/tetracycline master plate, incubate overnight at 37° and store the plate in the refrigerator. Test each isolate immediately for genetic markers and for spontaneous and induced reversion frequencies. Select the isolate with the best characteristics for the strain and make frozen permanents from a 12-hour oxoid nutrient broth culture. The spontaneous reversion frequency should be monitored frequently and should be 300 ± 60. There should be approximately 1,700 revertants per 100 µg of cumene hydroperoxide. Please keep in mind that TA102 master plates are not reliable for longer than 2 weeks.

We have found TA104 to be useful for the detection of some mutagenic aldehydes and hydroperoxides. Please see the table below for information about the strain. The ranges indicated for spontaneous reversion may be revised later as we gain more experience with TA104. A dose-response curve with cumene hydroperoxide is shown on page 7447 of Levin *et al.* (1982) A New *Salmonella* Tester Strain (TA102) with A·T Base Pairs at the Site of Mutation Detects Oxidative Mutagens, *PNAS 79,* 7445-7449.

Strain Designation	Genotype*	Spontaneous Revertants Per Plate		Positive Controls†	Induced Revertants Per Plate (-S9)
		-S9	+S9		
TA104	hisG428/Δ*uvrB*/*rfa*/pKM101	350±75	400±75	Crotonaldehyde	1,270/100 μg
				Methylglyoxal	12,200/50 μg

* In TA104, the hisG428 mutation is on the chromosome, whereas in TA102 the mutation is on a multicopy plasmid (Levin *PNAS 79,* 7445-7449).

† Methylglyoxal (Sigma) is a more potent mutagen than crotonaldehyde for TA104, but it is not diagnostic for the strain since it also reverts TA102 (2,600 revertants/50 μg). Kasai *et al.* (*Gann 73,* 681-683, 1982) reported the mutagenicity of methylglyoxal on TA100 (approx. 2,000 revertants/20 μg). Crotonaldehyde is also slightly mutagenic on TA100 (Eder *et al.*, *Xenobiotica 12,* 831-848, 1982), but we found it to be about 7 times more mutagenic on TA104. We are tentatively using crotonaldehyde (Aldrich) as the diagnostic mutagen for TA104 until we find a mutagen that is negative on the other tester strains.

Yours truly,

Bruce Ames

Bruce N. Ames
Professor of Biochemistry

BNA/dm
Enclosures